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<b>(21) International Application Number:</b> PCT/US98/18231 <b>(22) International Filing Date:</b> 1 September 1998 (01.09.98) <b>(30) Priority Data:</b> 60/056,033                      2 September 1997 (02.09.97)                      US <b>(71) Applicant (for all designated States except US):</b> WASHINGTON STATE UNIVERSITY RESEARCH FOUNDATION [US/US]; N.E. 1615 Eastgate Boulevard, Pullman, WA 99164-1802 (US). <b>(72) Inventors; and</b> <b>(75) Inventors/Applicants (for US only):</b> CROTEAU, Rodney, B. [US/US]; 1835 Northeast Valley Road, Pullman, WA 99163 (US). LANGE, Bernd, M. [DE/US]; 345 Northwest Irving Street #4, Pullman, WA 99163 (US). WILDUNG, Mark, R. [US/US]; 2252 Benedict Road, Colfax, WA 99111 (US). McCASKILL, David, G. [US/US]; P.O. Box 2375, Pullman, WA 99163 (US). <b>(74) Agent:</b> SHELTON, Dennis, K.; Christensen O'Connor Johnson & Kindness PLLC, Suite 2800, 1420 Fifth Avenue, Seattle, WA 98101 (US).		<b>(81) Designated States:</b> AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, GM, HR, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).  <b>Published</b> <i>With international search report.</i> <i>With amended claims.</i>
<b>(54) Title:</b> NUCLEIC AND AMINO ACID SEQUENCES FOR A NOVEL TRANSKETOLASE FROM <i>Mentha piperita</i> (MENTHA PIPERITA)		
<b>(57) Abstract</b> <p>cDNAs encoding 1-deoxyxylulose-5-phosphate synthase from peppermint <i>Mentha piperita</i> have been isolated and sequenced, and the corresponding amino acid sequences have been determined. Accordingly, isolated DNA sequences (SEQ ID NO:3, SEQ ID NO:5, SEQ ID NO:7) are provided which code for the expression of 1-deoxyxylulose-5-phosphate synthase from essential oil plant species. In other aspect the present invention provides for isolated, recombinant plant DXPS proteins, such as the proteins having the sequences set forth in SEQ ID NO:4, SEQ ID NO:6 and SEQ ID NO:8. In other aspects, replicable recombinant cloning vehicles are provided which code for plant 1-deoxyxylulose-5-phosphate synthases, or for a base sequence sufficiently complementary to at least a portion of 1-deoxyxylulose-5-phosphate synthase DNA or RNA to enable hybridization therewith. In yet other aspects, modified host cells are provided that have been transformed, transfected, infected and/or injected with a recombinant cloning vehicle and/or DNA sequence encoding a plant 1-deoxyxylulose-5-phosphate synthase. Thus, systems and methods are provided for the recombinant expression of the aforementioned recombinant 1-deoxyxylulose-5-phosphate synthase that may be used to facilitate its production, isolation and purification in significant amounts. Recombinant 1-deoxyxylulose-5-phosphate synthase may be used to obtain expression or enhanced expression of 1-deoxyxylulose-5-phosphate synthase in plants in order to enhance the production of 1-deoxyxylulose-5-phosphate, or its derivatives such as isopentenyl diphosphate (IPP), or may be otherwise employed for the regulation or expression of 1-deoxyxylulose-5-phosphate synthase, or the production of its products.</p>		

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NUCLEIC AND AMINO ACID SEQUENCES FOR A NOVEL TRANSKETOLASE FROM *Mentha piperita*

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Field of the Invention

The present invention relates to nucleic acid sequences which code for a novel transketolase from peppermint (*Mentha x piperita*), and to vectors containing the sequences, host cells containing the sequences and methods of upregulating or downregulating the production or activity of the transketolases and their mutants.

Background of the Invention

The isoprenoids comprise the largest family of natural products with over 20,000 individual compounds described to date (Connolly, J.D. & Hill, R.A., *Dictionary of Terpenoids* (Chapman and Hall, London, 1991)). The isoprenoids play numerous functional roles in plants as hormones (gibberellins, abscisic acid), photosynthetic pigments (side chain of phytol, carotenoids), electron carriers (side chain of plastoquinone), and structural components of membranes (phytosterols). Isoprenoids also serve in communication and defense, for example as attractants for pollinators and seed dispersers, and as competitive phytotoxins, antibiotics, and herbivore repellents and toxins (Harborne, J.B. in *Ecological Chemistry and Biochemistry of Plant Terpenoids* (Harborne, J.B., Tomas-Berberan, F.A., Eds.), pp. 399-426 (Clarendon Press, Oxford, 1991)).

Until recently, it was generally assumed that all isoprenoids were synthesized from acetyl-CoA via the classical mevalonate pathway (Spurgeon, S.L. & Porter, J.W., Eds., in *Biosynthesis of Isoprenoid Compounds*, Vol. 1, pp 1-46 (John Wiley,

New York, 1983)). However, in 1993, Rohmer and co-workers (Rohmer, M. et al., *Biochem. J.* **295**:517-524 (1993)) demonstrated that a non-mevalonate pathway, originating from pyruvate and glyceraldehyde-3-phosphate (GAP) (Rohmer, M. et al., *J. Am. Chem. Soc.* **118**:2564-2566 (1996)), operated in several eubacteria, including  
5 *E. coli*. Evidence subsequently emerged that the plastid-derived isoprenoids of plants, including carotenoids and the prenyl side chains of chlorophyll and plastoquinone (Lichtenthaler, H.K. et al., *FEBS Lett.* **400**:271-274 (1997)), as well as isoprene (Zeidler J.G. et al., *Z. Naturforsch.* **52c**:15-23 (1997)), monoterpenes (Eisenreich, W. et al., *Tetrahedron Lett.* **38**:3889-3892 (1997)) and diterpenes (Eisenreich, W. et al.,  
10 *Proc. Natl. Acad. Sci. USA* **93**:6431-6436 (1996)); (Schwarz, M.K., PhD thesis, ETH, Zurich, Switzerland (1994)), are synthesized via the pyruvate/GAP route to isopentenyl diphosphate (IPP). This new pathway had been completely overlooked in the past.

The first dedicated reaction of this new enzymatic pathway to IPP is  
15 considered to involve a transketolase-type condensation involving pyruvate and GAP to form 1-deoxy-D-xylulose-5-phosphate (Rohmer, M. et al., *J. Am. Chem. Soc.* **118**:2564-2566 (1996)); (Zeidler J.G. et al., *Z. Naturforsch.* **52c**:15-23 (1997)); (Broers, S.T.J., PhD thesis, ETH, Zurich, Switzerland (1994)) (FIGURE 1). A recent abstract has described the cloning of a gene encoding 1-deoxyxylulose-5-phosphate  
20 synthase from *E. coli*, but no sequence information, or other descriptive information, was reported (Lois, L.M. et al., Third Terpnnet Meeting of the European Network on Plant Isoprenoids, Poitiers, France, May 29-30 (1997)).

#### Summary of the Invention

In accordance with the present invention, isolated nucleic acid sequences, such  
25 as the sequences set forth in SEQ ID NO:1, SEQ ID NO:2, SEQ ID NO:3, SEQ ID NO:5 and SEQ ID NO:7 which encode all or part of a 1-deoxyxylulose-5-phosphate synthase (abbreviated as *DXPS*) from peppermint (*Mentha x piperita*) have been isolated, identified and characterized. Thus, the present invention provides nucleic acid sequences encoding essential oil plant 1-deoxyxylulose-5-phosphate synthase  
30 proteins. In particular, the present invention provides nucleic acid sequences encoding 1-deoxyxylulose-5-phosphate synthase proteins from the family Lamiaceae. In another aspect the present invention provides for isolated, recombinant plant DXPS proteins, such as the proteins having the sequences set forth in SEQ ID NO:4, SEQ ID NO:6 and SEQ ID NO:8. In other aspects, the present invention is directed to  
35 replicable recombinant cloning vehicles comprising a nucleic acid sequence, e.g., a

DNA sequence, which codes for *DXPS* or for a base sequence sufficiently complementary to at least a portion of the *DXPS* DNA or RNA to enable hybridization therewith (e.g., antisense transketolase RNA or fragments of complementary transketolase DNA which are useful as polymerase chain reaction primers or as probes for transketolases from *Mentha x piperita* or related genes). In yet other aspects of the invention, modified host cells are provided that have been transformed, transfected, infected and/or injected with a recombinant cloning vehicle and/or DNA sequence of the invention. Thus, the present invention provides for the recombinant expression of the transketolase 1-deoxyxylulose-5-phosphate synthase (*DXPS*) from peppermint (*Mentha x piperita*) and related transketolases from plants, and the inventive concepts may be used to facilitate the production, isolation and purification of significant quantities of recombinant plant transketolases (or of the primary enzyme products) for subsequent use, such as to obtain expression or enhanced expression of transketolases in plants to attain enhanced production of predator or pathogen defense compounds, or may be otherwise employed in an environment where the regulation or expression of transketolases are desired. In other aspects, the regulation of isoprenoid biosynthesis in plants by transforming, transfecting, infecting and/or injecting the plant with a recombinant cloning vehicle and/or DNA sequence of the invention to obtain expression of the transketolase *DXPS* or a related transketolase in the plant and thereby upregulate the pyruvate/glyceraldehyde-3-phosphate isoprenoid biosynthetic pathway. Thus, in addition to the new nucleic acid sequences and fragments thereof, the present invention includes new vectors containing the sequences, host cells containing the sequences, isolated recombinant transketolase (synthase) polypeptides and methods of producing recombinant transketolases and their mutants.

#### Brief Description of the Drawings

The foregoing aspects and many of the attendant advantages of this invention will be better understood by reference to the following detailed description, when taken in conjunction with the accompanying drawings, wherein:

FIGURE 1 is a schematic representation of the enzymatic pathway from pyruvate to isopentenyl diphosphate (IPP) as catalyzed by 1-deoxyxylulose-5-phosphate synthase (*DXPS*). The addition of thiamin pyrophosphate (TPP)-activated acetaldehyde, formed by decarboxylation of pyruvate, to C1 of glyceraldehyde-3-phosphate (GAP) and subsequent loss of TPP yields 1-deoxyxylulose-5-phosphate, which ultimately gives rise to isopentenyl diphosphate (IPP).

FIGURE 2A shows a GC-MS analysis of the product formed by the recombinant *DXPS* peppermint enzyme. Mass fragmentation patterns are illustrated for the biosynthetic product after dephosphorylation and trimethylsilylation ( $R_t = 6.71$  min).

5 FIGURE 2B shows a GC-MS analysis of the silylated derivative of authentic 1-deoxy-*D*-xylulose ( $R_t = 6.70$  min).

FIGURE 3 is a graphical representation of the time-course of relative steady-state *DXPS* mRNA levels (-●-) and rate of monoterpene biosynthesis as measured by  $^{14}\text{CO}_2$  incorporation (-○-) during leaf development in peppermint. Total RNA was isolated from oil gland secretory cells of leaves of different developmental stages. A  $^{32}\text{P}$ -labeled probe derived from *DXPS* clone pDS29 (SEQ ID NO:5) detected a transcript of about 3 kb. Leaves are fully expanded by two weeks, and high rates of monoterpene biosynthesis and high steady-state levels of *DXPS* mRNA are observed only during early leaf development (< 7 d).

15 FIGURE 4 shows the results of clustering relationship analysis based on sequence comparisons carried out using GCG version 9.0 of the University of Wisconsin Genetics Computer Group Package (1997). The following transketolase sequences are included: *DXPS* (*Mentha x piperita*, accession number AF019383), *CLA1* (*Arabidopsis thaliana*, U27099), *ORF2814* (*Rhodobacter capsulata*, P26242), *ORF620* (*Escherichia coli*, U82664), a protein of unknown function (*Synechocystis* sp. PC6803, D90903), transketolase 1 (human, A45050; yeast P23254; *Escherichia coli*, P27302), transketolase 2 (human, P51854; yeast, P33315; *Escherichia coli*, P33570), and a plastidial transketolase from potato (Z50099).

#### Detailed Description of the Preferred Embodiment

25 As used herein, the terms "amino acid" and "amino acids" refer to all naturally occurring L- $\alpha$ -amino acids or their residues. The amino acids are identified by either the single-letter or three-letter designations:

30	Asp	D	aspartic acid	Ile	I	isoleucine
	Thr	T	threonine	Leu	L	leucine
	Ser	S	serine	Tyr	Y	tyrosine
	Glu	E	glutamic acid	Phe	F	phenylalanine
	Pro	P	proline	His	H	histidine
	Gly	G	glycine	Lys	K	lysine
	Ala	A	alanine	Arg	R	arginine
35	Cys	C	cysteine	Trp	W	tryptophan

Val V valine  
Met M methionine

Gln Q glutamine  
Asn N asparagine

As used herein, the term "nucleotide" means a monomeric unit of DNA or RNA containing a sugar moiety (pentose), a phosphate and a nitrogenous heterocyclic base. The base is linked to the sugar moiety via the glycosidic carbon (1' carbon of pentose) and that combination of base and sugar is called a nucleoside. The base characterizes the nucleotide with the four bases of DNA being adenine ("A"), guanine ("G"), cytosine ("C") and thymine ("T"). Inosine ("I") is a synthetic base that can be used to substitute for any of the four, naturally-occurring bases (A, C, G or T). The four RNA bases are A, G, C and uracil ("U"). The nucleotide sequences described herein comprise a linear array of nucleotides connected by phosphodiester bonds between the 3' and 5' carbons of adjacent pentoses.

"Oligonucleotide" refers to short length single or double stranded sequences of deoxyribonucleotides linked via phosphodiester bonds. The oligonucleotides are chemically synthesized by known methods and purified, for example, on polyacrylamide gels.

The term "1-deoxyxylulose-5-phosphate synthase" (abbreviated as "DXPS") is used herein to mean an enzyme capable of catalyzing a transketolase-type condensation involving pyruvate and glyceraldehyde-3-phosphate (GAP) to form 1-deoxy-D-xylulose-5-phosphate. This reaction is schematically set forth in FIGURE 1.

The term "essential oil plant," or "essential oil plants," refers to a group of plant species that produce high levels of monoterpenoid and/or sesquiterpenoid and/or diterpenoid oils, and/or high levels of monoterpenoid and/or sesquiterpenoid and/or diterpenoid resins. The foregoing oils and/or resins account for greater than about 0.005% of the fresh weight of an essential oil plant that produces them. The essential oils and/or resins are more fully described, for example, in *E. Guenther, The Essential Oils, Vols. I-VI, R.E. Krieger Publishing Co., Huntington N.Y., 1975*, incorporated herein by reference. The essential oil plants include, but are not limited to:

Lamiaceae, including, but not limited to, the following species: Ocimum (basil), Lavandula (Lavender), Origanum (oregano), Mentha (mint), Salvia (sage), Rosmecinus (rosemary), Thymus (thyme), Satureja and Monarda.

Umbelliferae, including, but not limited to, the following species: Carum (caraway), Anethum (dill), feniculum (fennel) and Daucus (carrot).

Asteraceae (Compositae), including, but not limited to, the following species: Artemisia (tarragon, sage brush), Tanacetum (tansy).

Rutaceae (e.g., citrus plants); Rosaceae (e.g., roses); Myrtaceae (e.g., eucalyptus, Melaleuca); the Gramineae (e.g., Cymbopogon (citronella)); Geranaceae (Geranium) and certain conifers including Abies (e.g., Canadian balsam), Cedrus (cedar) and Thuja and Juniperus.

The range of essential oil plants is more fully set forth in *E. Guenther, The Essential Oils, Vols. I-VI, R.E. Krieger Publishing Co., Huntington N.Y., 1975*, which is incorporated herein by reference.

Abbreviations used are: bp, base pair; DMAPP, dimethylallyl diphosphate; DXPS, 1-deoxyxylulose-5-phosphate synthase; GAP, glyceraldehyde-3-phosphate; IPP, isopentenyl diphosphate; ; Mopso, 3-(N-morpholino)-2-hydroxypropane-sulfonic acid; Tris, Tris-(hydroxymethyl)aminomethane; UTR, untranslated region; TLC, thin layer chromatography; Tr, truncation site; GC, gas chromatography; Hepes, N-2-hydroxyethylpiperazine-N'-2-ethanesulfonic acid; kb, kilobase pairs.

The abbreviation "SSC" refers to a buffer used in nucleic acid hybridization solutions. One liter of the 20X (twenty times concentrate) stock SSC buffer solution (pH 7.0) contains 175.3 g sodium chloride and 88.2 g sodium citrate.

The terms "alteration", "amino acid sequence alteration", "variant" and "amino acid sequence variant" refer to 1-deoxyxylulose-5-phosphate synthase molecules with some differences in their amino acid sequences as compared to the corresponding, native, i.e., naturally-occurring, 1-deoxyxylulose-5-phosphate synthases. Ordinarily, the variants will possess at least about 70% homology with the corresponding native 1-deoxyxylulose-5-phosphate synthases, and preferably they will be at least about 80% homologous with the corresponding, native 1-deoxyxylulose-5-phosphate synthases. The amino acid sequence variants of the 1-deoxyxylulose-5-phosphate synthases falling within this invention possess substitutions, deletions, and/or insertions at certain positions. Sequence variants of 1-deoxyxylulose-5-phosphate synthases may be used to attain desired enhanced or reduced enzymatic activity, modified regiochemistry or stereochemistry, or altered substrate utilization or product distribution.

Substitutional 1-deoxyxylulose-5-phosphate synthase variants are those that have at least one amino acid residue in the native 1-deoxyxylulose-5-phosphate synthase sequence removed and a different amino acid inserted in its place at the same position. The substitutions may be single, where only one amino acid in the molecule



has been substituted, or they may be multiple, where two or more amino acids have been substituted in the same molecule. Substantial changes in the activity of the 1-deoxyxylulose-5-phosphate synthase molecules of the present invention may be obtained by substituting an amino acid with a side chain that is significantly different in charge and/or structure from that of the native amino acid. This type of substitution would be expected to affect the structure of the polypeptide backbone and/or the charge or hydrophobicity of the molecule in the area of the substitution.

Moderate changes in the activity of the 1-deoxyxylulose-5-phosphate synthase molecules of the present invention would be expected by substituting an amino acid with a side chain that is similar in charge and/or structure to that of the native molecule. This type of substitution, referred to as a conservative substitution, would not be expected to substantially alter either the structure of the polypeptide backbone or the charge or hydrophobicity of the molecule in the area of the substitution.

Insertional 1-deoxyxylulose-5-phosphate synthase variants are those with one or more amino acids inserted immediately adjacent to an amino acid at a particular position in the native 1-deoxyxylulose-5-phosphate synthase molecule. Immediately adjacent to an amino acid means connected to either the  $\alpha$ -carboxy or  $\alpha$ -amino functional group of the amino acid. The insertion may be one or more amino acids. Ordinarily, the insertion will consist of one or two conservative amino acids. Amino acids similar in charge and/or structure to the amino acids adjacent to the site of insertion are defined as conservative. Alternatively, this invention includes insertion of an amino acid with a charge and/or structure that is substantially different from the amino acids adjacent to the site of insertion.

Deletional variants are those where one or more amino acids in the native 1-deoxyxylulose-5-phosphate synthase molecules have been removed. Ordinarily, deletional variants will have one or two amino acids deleted in a particular region of the 1-deoxyxylulose-5-phosphate synthase molecule.

The terms "biological activity", "biologically active", "activity" and "active" refer to the ability of the 1-deoxyxylulose-5-phosphate synthases of the present invention to catalyze a transketolase-type condensation involving pyruvate and glyceraldehyde-3-phosphate (GAP) to form 1-deoxy-*D*-xylulose-5-phosphate. This reaction is schematically set forth in FIGURE 1. 1-deoxyxylulose-5-phosphate synthase activity is measured in an enzyme activity assay, such as the assay described in Example 2. Amino acid sequence variants of the 1-deoxyxylulose-5-phosphate synthases of the present invention may have desirable altered biological activity

including, for example, altered reaction kinetics, substrate utilization, product distribution or other characteristics such as regiochemistry and stereochemistry.

The terms "DNA sequence encoding", "DNA encoding" and "nucleic acid encoding" refer to the order or sequence of deoxyribonucleotides along a strand of deoxyribonucleic acid. The order of these deoxyribonucleotides determines the order of amino acids along the translated polypeptide chain. The DNA sequence thus codes for the amino acid sequence.

The terms "replicable expression vector" and "expression vector" refer to a piece of DNA, usually double-stranded, which may have inserted into it a piece of DNA (the insert DNA) from another source. The vector is used to transport the insert DNA into a suitable host cell. The insert DNA may be derived from the host cell, or may be derived from a different cell or organism. Once in the host cell, the vector can replicate independently of or coincidental with the host chromosomal DNA, and several copies of the vector and its inserted DNA may be generated. In addition, the vector contains the necessary elements that permit translating the insert DNA into a polypeptide. Many molecules of the polypeptide encoded by the insert DNA can thus be rapidly synthesized.

The terms "transformed host cell," "transformed" and "transformation" refer to the introduction of DNA into a cell. The cell is termed a "host cell", and it may be a prokaryotic or a eukaryotic cell. Typical prokaryotic host cells include various strains of *E. coli*. Typical eukaryotic host cells are plant cells, such as maize cells, yeast cells, insect cells or animal cells. The introduced DNA is usually in the form of a vector containing an inserted piece of DNA. The introduced DNA sequence may be from the same species as the host cell or from a different species from the host cell, or it may be a hybrid DNA sequence, containing some foreign DNA and some DNA derived from the host species.

In accordance with the present invention, total RNA was extracted from secretory cells which had been isolated from 5-day-old peppermint leaves. Poly(A)<sup>+</sup>-RNA was purified by chromatography on oligo(dT)-cellulose (Pharmacia), and 5 µg of the resulting mRNA was utilized to construct a λZAP cDNA library. One hundred and fifty randomly picked and purified clones were *in vivo*-excised and the resulting phagemids were sequenced using T3 and T7 primers. Two clones (designated pDS1 and pDS2) were identified which exhibited significant sequence similarity to a recently described *Arabidopsis thaliana* transketolase gene of unknown function (*CLAI*). The

nucleotide sequence of the cDNA insert of pDS1 is set forth in SEQ ID NO:1, and the nucleotide sequence of the cDNA insert of pDS2 is set forth in SEQ ID NO:2.

A set of 3,000 plaques was then screened with a nucleic acid probe (SEQ ID NO:9) derived by PCR from the cDNA insert (SEQ ID NO:1) of pDS1. This procedure afforded 47 positive signals under high-stringency hybridization conditions. After one additional cycle of hybridization, the positive clones were *in vivo*-excised, the insert sizes were determined by PCR, and the 20 largest clones were partially sequenced. Three of these clones (designated pDS16, pDS29 and pDS39) appeared to be of full-length and were entirely sequenced on both strands. The nucleotide sequence of the cDNA insert of pDS16 is set forth in SEQ ID NO:3, the nucleotide sequence of the cDNA insert of pDS29 is set forth in SEQ ID NO:5 and the nucleotide sequence of the cDNA insert of pDS39 is set forth in SEQ ID NO:7.

The cDNA insert of *DXPS* clone pDS29 (SEQ ID NO:5), which yielded the highest expressed level of synthase activity, contains an open reading frame (ORF) of 2172 nucleotides. The first 70 deduced amino acid residues (amino acid residues 1-70 of SEQ ID NO:6) show the general characteristics of plastidial targeting sequences, consistent with the proposed subcellular location of the enzyme in plant cells. By excluding the putative transit peptide residues, the sequence corresponds to a mature protein of about 650 amino acids, with a predicted size of roughly 71 kDa. An alignment of translated transketolase sequences (devoid of plastid-targeting peptides where appropriate) shows very high similarity/identity values between the peppermint *DXPS* and several other transketolases.

*E. coli* cultures transfected with phagemids derived from pDS16, including the cDNA sequence set forth in SEQ ID NO:3, pDS29, including the cDNA sequence set forth in SEQ ID NO:5, and pDS39, including the cDNA sequence set forth in SEQ ID NO:7, were each induced with isopropyl-1 thio- $\beta$ -D-galactopyranoside (IPTG), the corresponding bacterial cells were harvested and homogenized, and the extracts were assayed using [2- $^{14}$ C] pyruvate and *D,L*-glyceraldehyde-3 phosphate as co-substrates. Preparations from *E. coli* cells transfected with pDS29, including the cDNA sequence set forth in SEQ ID NO:5, and pDS39, including the cDNA sequence set forth in SEQ ID NO:7, yielded a prominent new radioactive component in the reaction mixture that, upon reversed-phase ion-pair radio-HPLC, exhibited a  $R_t$  (35.5 min) consistent with that of a sugar (pentulose) phosphate. The same enzymatic product was generated with *D*-glyceraldehyde-3-phosphate as co-substrate, indicating that the *D*-antipode is the likely natural substrate of the functionally expressed transketolase.

The presumptive pentulose phosphate product from preparative enzyme incubations (*E. coli* transformed with pDS29, including the cDNA sequence set forth in SEQ ID NO:5) was purified by HPLC and hydrolyzed with acid phosphatase, and the resulting sugar was silylated. This derivatized product of the recombinant enzyme was then  
5 analyzed by combined capillary GC-MS and shown to possess the identical retention time ( $6.71 \pm 0.03$  min) and mass spectrum as that of an authentic sample of silylated 1-deoxy-*D*-xylulose (FIGURES 2A and 2B). The combined evidence thus indicated that a cDNA encoding 1-deoxyxylulose-5-phosphate synthase (*DXPS*) had been acquired. *DXPS* activity was significantly higher in the IPTG-induced *E. coli* cells  
10 expressing the cDNA insert of pDS29 (SEQ ID NO:5), when compared to identically treated cells containing the same plasmid devoid of the cDNA insert set forth in SEQ ID NO:5 (7-fold higher than endogenous activity,  $n = 7$ ,  $p < 0.01$ ).

RNA blot analyses showed a direct correlation between steady-state levels of the *DXPS* message and monoterpene production, as determined by CO<sub>2</sub>  
15 incorporation, thus suggesting activation of the non-mevalonate pathway to supply the IPP precursor for subsequent monoterpene biosynthesis in peppermint oil glands (FIGURE 3).

The isolation of full-length cDNAs (SEQ ID NO:3, SEQ ID NO:5, SEQ ID NO:7) encoding 1-deoxyxylulose-5-phosphate synthase permits the development of  
20 efficient expression systems for this functional enzyme; provides useful tools for examining the developmental regulation of *DXPS*; permits investigation of the reaction mechanism(s) of this enzyme, and permits the isolation of other 1-deoxyxylulose-5-phosphate synthases. The isolation of full-length 1-deoxyxylulose-5-phosphate synthase cDNAs (SEQ ID NO:3, SEQ ID NO:5, SEQ ID NO:7) also  
25 permits the transformation of a wide range of organisms in order to enhance, or otherwise alter, the synthesis of 1-deoxyxylulose-5-phosphate, and of its derivatives, such as IPP.

Although the full-length 1-deoxyxylulose-5-phosphate synthase proteins set forth in (SEQ ID NO:4, SEQ ID NO:6, SEQ ID NO:8) directs the enzyme to plastids,  
30 substitution of the presumptive targeting sequence of this enzyme (e.g., SEQ ID NO:3, amino acid residue numbers 1 to 70) with other transport sequences well known in the art (see, e.g., von Heijne et al., *Eur. J. Biochem.*, **180**:535-545, 1989; Stryer, *Biochemistry*, W.H. Freeman and Company, New York, NY, p. 769 [1988]) may be employed to direct 1-deoxyxylulose-5-phosphate synthase to other cellular or  
35 extracellular locations.

In addition to the native 1-deoxyxylulose-5-phosphate synthase amino acid sequences of SEQ ID NO:4, SEQ ID NO:6, SEQ ID NO:8, sequence variants produced by deletions, substitutions, mutations and/or insertions are intended to be within the scope of the invention except insofar as limited by the prior art. The 1-deoxyxylulose-5-phosphate synthase amino acid sequence variants of this invention may be constructed by mutating the DNA sequences that encode the wild-type synthases, such as by using techniques commonly referred to as site-directed mutagenesis. Nucleic acid molecules encoding the 1-deoxyxylulose-5-phosphate synthases of the present invention can be mutated by a variety of PCR techniques well known to one of ordinary skill in the art. (See, for example, the following publications, the cited portions of which are incorporated by reference herein: "PCR Strategies", M.A. Innis, D.H. Gelfand and J.J. Sninsky, eds., 1995, Academic Press, San Diego, CA (Chapter 14); "PCR Protocols: A Guide to Methods and Applications", M.A. Innis, D.H. Gelfand, J.J. Sninsky and T.J. White, eds., Academic Press, NY (1990).

By way of non-limiting example, the two primer system utilized in the Transformer Site-Directed Mutagenesis kit from Clontech, may be employed for introducing site-directed mutants into the 1-deoxyxylulose-5-phosphate synthase genes of the present invention. Following denaturation of the target plasmid in this system, two primers are simultaneously annealed to the plasmid; one of these primers contains the desired site-directed mutation, the other contains a mutation at another point in the plasmid resulting in elimination of a restriction site. Second strand synthesis is then carried out, tightly linking these two mutations, and the resulting plasmids are transformed into a *mutS* strain of *E. coli*. Plasmid DNA is isolated from the transformed bacteria, restricted with the relevant restriction enzyme (thereby linearizing the unmutated plasmids), and then retransformed into *E. coli*. This system allows for generation of mutations directly in an expression plasmid, without the necessity of subcloning or generation of single-stranded phagemids. The tight linkage of the two mutations and the subsequent linearization of unmutated plasmids results in high mutation efficiency and allows minimal screening. Following synthesis of the initial restriction site primer, this method requires the use of only one new primer type per mutation site. Rather than prepare each positional mutant separately, a set of "designed degenerate" oligonucleotide primers can be synthesized in order to introduce all of the desired mutations at a given site simultaneously. Transformants can be screened by sequencing the plasmid DNA through the mutagenized region to

identify and sort mutant clones. Each mutant DNA can then be fully sequenced or restricted and analyzed by electrophoresis on Mutation Detection Enhancement gel (J.T. Baker) to confirm that no other alterations in the sequence have occurred (by band shift comparison to the unmutagenized control).

5        Again, by way of non-limiting example, the two primer system utilized in the QuikChange™ Site-Directed Mutagenesis kit from Stratagene (LaJolla, California), may be employed for introducing site-directed mutants into the 1-deoxyxylulose-5-phosphate synthase genes of the present invention. Double-stranded plasmid DNA, containing the insert bearing the target mutation site, is denatured and mixed with two  
10    oligonucleotides complementary to each of the strands of the plasmid DNA at the target mutation site. The annealed oligonucleotide primers are extended using *Pfu* DNA polymerase, thereby generating a mutated plasmid containing staggered nicks. After temperature cycling, the unmutated, parental DNA template is digested with restriction enzyme *DpnI* which cleaves methylated or hemimethylated DNA, but  
15    which does not cleave unmethylated DNA. The parental, template DNA is almost always methylated or hemimethylated since most strains of *E.coli*, from which the template DNA is obtained, contain the required methylase activity. The remaining, annealed vector DNA incorporating the desired mutation(s) is transformed into *E. coli*.

20        The sequence verified mutant duplexes in the pET (or other) overexpression vector can be employed to transform *E. coli* such as strain *E. coli* BL21(DE3)pLysS, for high level production of the mutant protein, and purification by standard protocols. The method of FAB-MS mapping can be employed to rapidly check the fidelity of mutant expression. This technique provides for sequencing segments  
25    throughout the whole protein and provides the necessary confidence in the sequence assignment. In a mapping experiment of this type, protein is digested with a protease (the choice will depend on the specific region to be modified since this segment is of prime interest and the remaining map should be identical to the map of unmutagenized protein). The set of cleavage fragments is fractionated by microbore HPLC (reversed  
30    phase or ion exchange, again depending on the specific region to be modified) to provide several peptides in each fraction, and the molecular weights of the peptides are determined by FAB-MS. The masses are then compared to the molecular weights of peptides expected from the digestion of the predicted sequence, and the correctness of the sequence quickly ascertained. Since this mutagenesis approach to protein  
35    modification is directed, sequencing of the altered peptide should not be necessary if

the MS agrees with prediction. If necessary to verify a changed residue, CAD-tandem MS/MS can be employed to sequence the peptides of the mixture in question, or the target peptide purified for subtractive Edman degradation or carboxypeptidase Y digestion depending on the location of the modification.

5 In the design of a particular site directed mutagenesis, it is generally desirable to first make a non-conservative substitution (e.g., Ala for Cys, His or Glu) and determine if activity is greatly impaired as a consequence. The properties of the mutagenized protein are then examined with particular attention to the kinetic parameters of  $K_m$  and  $k_{cat}$  as sensitive indicators of altered function, from which  
10 changes in binding and/or catalysis *per se* may be deduced by comparison to the native enzyme. If the residue is by this means demonstrated to be important by activity impairment, or knockout, then conservative substitutions can be made, such as Asp for Glu to alter side chain length, Ser for Cys, or Arg for His.

Other site directed mutagenesis techniques may also be employed with the  
15 nucleotide sequences of the invention. For example, restriction endonuclease digestion of DNA followed by ligation may be used to generate deletion variants of 1-deoxyxylulose-5-phosphate synthase, as described in section 15.3 of Sambrook et al. *Molecular Cloning: A Laboratory Manual*, 2nd Ed., Cold Spring Harbor Laboratory Press, New York, NY [1989], incorporated herein by reference. A similar strategy  
20 may be used to construct insertion variants, as described in section 15.3 of Sambrook et al., *supra*.

Oligonucleotide-directed mutagenesis may also be employed for preparing substitution variants of this invention. It may also be used to conveniently prepare the deletion and insertion variants of this invention. This technique is well known in the  
25 art as described by Adelman et al. (*DNA* 2:183 [1983]); Sambrook et al., *supra*; "Current Protocols in Molecular Biology", 1991, Wiley (NY), F.T. Ausubel, R. Brent, R.E. Kingston, D.D. Moore, J.D. Seidman, J.A. Smith and K. Struhl, eds, incorporated herein by reference.

Generally, oligonucleotides of at least 25 nucleotides in length are used to  
30 insert, delete or substitute two or more nucleotides in the 1-deoxyxylulose-5-phosphate synthase molecule. An optimal oligonucleotide will have 12 to 15 perfectly matched nucleotides on either side of the nucleotides coding for the mutation. To mutagenize wild-type 1-deoxyxylulose-5-phosphate synthase, the oligonucleotide is annealed to the single-stranded DNA template molecule under suitable hybridization  
35 conditions. A DNA polymerizing enzyme, usually the Klenow fragment of *E. coli*

DNA polymerase I, is then added. This enzyme uses the oligonucleotide as a primer to complete the synthesis of the mutation-bearing strand of DNA. Thus, a heteroduplex molecule is formed such that one strand of DNA encodes the wild-type synthase inserted in the vector, and the second strand of DNA encodes the mutated form of the synthase inserted into the same vector. This heteroduplex molecule is then transformed into a suitable host cell.

Mutants with more than one amino acid substituted may be generated in one of several ways. If the amino acids are located close together in the polypeptide chain, they may be mutated simultaneously using one oligonucleotide that codes for all of the desired amino acid substitutions. If, however, the amino acids are located some distance from each other (separated by more than ten amino acids, for example) it is more difficult to generate a single oligonucleotide that encodes all of the desired changes. Instead, one of two alternative methods may be employed. In the first method, a separate oligonucleotide is generated for each amino acid to be substituted. The oligonucleotides are then annealed to the single-stranded template DNA simultaneously, and the second strand of DNA that is synthesized from the template will encode all of the desired amino acid substitutions. An alternative method involves two or more rounds of mutagenesis to produce the desired mutant. The first round is as described for the single mutants: wild-type 1-deoxyxylulose-5-phosphate synthase DNA is used for the template, an oligonucleotide encoding the first desired amino acid substitution(s) is annealed to this template, and the heteroduplex DNA molecule is then generated. The second round of mutagenesis utilizes the mutated DNA produced in the first round of mutagenesis as the template. Thus, this template already contains one or more mutations. The oligonucleotide encoding the additional desired amino acid substitution(s) is then annealed to this template, and the resulting strand of DNA now encodes mutations from both the first and second rounds of mutagenesis. This resultant DNA can be used as a template in a third round of mutagenesis, and so on.

A gene encoding 1-deoxyxylulose-5-phosphate synthase may be incorporated into any organism (intact plant, animal, microbe, etc.), or cell culture derived therefrom. A 1-deoxyxylulose-5-phosphate synthase gene may be introduced into any organism for a variety of purposes including, but not limited to: production of 1-deoxyxylulose-5-phosphate synthase, or its product 1-deoxyxylulose-5-phosphate; enhancement of the rate of production and/or the absolute amount of one or more chemical compounds, such as IPP, derived from 1-deoxyxylulose-5-phosphate;



augmenting the disease resistance of plants by enhancing the production of terpenoid(s) having defensive, e.g., antimicrobial or antifeedant, properties. Additionally, a gene encoding all or part of a 1-deoxyxylulose-5-phosphate synthase can be introduced, in antisense orientation, into any plant species in order to reduce the amount of 1-deoxyxylulose-5-phosphate synthase produced in the plant, thereby reducing the production of terpenoids.

Additionally, because the novel pathway involving the DXPS enzymes of the present invention is present in certain bacteria and plants, but not in animals, it provides a new molecular target for the design of highly specific antibiotics and herbicides. Thus, analysis of the structure and catalytic mechanism of DXPS proteins of the present invention will lead to the development of selective inhibitors of this enzyme having antibiotic and/or herbicidal activity. Once selective inhibitors of the DXPS proteins of the present invention have been identified, mutagenesis of the nucleic acid molecules encoding DXPS proteins of the present invention will yield inhibitor-resistant DXPS proteins. Nucleic acid sequences encoding these inhibitor-resistant DXPS proteins can be introduced into plants, thereby producing transgenic plants that are resistant to the DXPS inhibitors. Thus, for example, transgenic grass species used in lawns can be transformed with a nucleic acid sequence encoding inhibitor-resistant DXPS protein; thereafter treatment of the lawn with a DXPS inhibitor will kill unwanted weeds, but leave the transformed, DXPS-resistant grass unharmed.

Eukaryotic expression systems may be utilized for the production of 1-deoxyxylulose-5-phosphate synthase since they are capable of carrying out any required posttranslational modifications and of directing the enzyme to the proper cellular compartment. A representative eukaryotic expression system for this purpose uses the recombinant baculovirus, *Autographa californica* nuclear polyhedrosis virus (AcNPV; M.D. Summers and G.E. Smith, *A Manual of Methods for Baculovirus Vectors and Insect Cell Culture Procedures* [1986]; Luckow et al., *Bio-technology*, 6:47-55 [1987]) for expression of the 1-deoxyxylulose-5-phosphate synthases of the invention. Infection of insect cells (such as cells of the species *Spodoptera frugiperda*) with the recombinant baculoviruses allows for the production of large amounts of the 1-deoxyxylulose-5-phosphate synthase proteins. In addition, the baculovirus system has other important advantages for the production of recombinant 1-deoxyxylulose-5-phosphate synthase. For example, baculoviruses do not infect humans and can therefore be safely handled in large quantities. In the baculovirus

system, a DNA construct is prepared including a DNA segment encoding 1-deoxyxylulose-5-phosphate synthase and a vector. The vector may comprise the polyhedron gene promoter region of a baculovirus, the baculovirus flanking sequences necessary for proper cross-over during recombination (the flanking sequences  
5 comprise about 200-300 base pairs adjacent to the promoter sequence) and a bacterial origin of replication which permits the construct to replicate in bacteria. The vector is constructed so that (i) the DNA segment is placed adjacent (or operably linked or "downstream" or "under the control of") to the polyhedron gene promoter and (ii) the promoter/1-deoxyxylulose-5-phosphate synthase combination is flanked on both sides  
10 by 200-300 base pairs of baculovirus DNA (the flanking sequences).

To produce the 1-deoxyxylulose-5-phosphate synthase DNA construct, a cDNA clone encoding the full length 1-deoxyxylulose-5-phosphate synthase is obtained using methods such as those described herein. The DNA construct is contacted in a host cell with baculovirus DNA of an appropriate baculovirus (that is,  
15 of the same species of baculovirus as the promoter encoded in the construct) under conditions such that recombination is effected. The resulting recombinant baculoviruses encode the full 1-deoxyxylulose-5-phosphate synthase. For example, an insect host cell can be cotransfected or transfected separately with the DNA construct and a functional baculovirus. Resulting recombinant baculoviruses can then be  
20 isolated and used to infect cells to effect production of the 1-deoxyxylulose-5-phosphate synthase. Host insect cells include, for example, *Spodoptera frugiperda* cells, that are capable of producing a baculovirus-expressed 1-deoxyxylulose-5-phosphate synthase. Insect host cells infected with a recombinant baculovirus of the present invention are then cultured under conditions allowing expression of the  
25 baculovirus-encoded 1-deoxyxylulose-5-phosphate synthase. 1-deoxyxylulose-5-phosphate synthase thus produced is then extracted from the cells using methods known in the art.

Other eukaryotic microbes such as yeasts may also be used to practice this invention. The baker's yeast *Saccharomyces cerevisiae*, is a commonly used yeast;  
30 although several other strains are available. The plasmid YRp7 (Stinchcomb et al., *Nature*, **282**:39 [1979]; Kingsman et al., *Gene* **7**:141 [1979]; Tschemper et al., *Gene*, **10**:157 [1980]) is commonly used as an expression vector in *Saccharomyces*. This plasmid contains the *trp1* gene that provides a selection marker for a mutant strain of yeast lacking the ability to grow in tryptophan, such as strains ATCC No. 44,076 and  
35 PEP4-1 (Jones, *Genetics*, **85**:12 [1977]). The presence of the *trp1* lesion as a

characteristic of the yeast host cell genome then provides an effective environment for detecting transformation by growth in the absence of tryptophan. Yeast host cells are generally transformed using the polyethylene glycol method, as described by Hinnen (*Proc. Natl. Acad. Sci. USA*, 75:1929 [1978]). Additional yeast transformation  
5 protocols are set forth in Gietz et al., *N.A.R.*, 20(17):1425(1992); Reeves et al., *FEMS*, 99(2-3):193-197, (1992), both of which references are incorporated herein by reference.

Suitable promoting sequences in yeast vectors include the promoters for 3-phosphoglycerate kinase (Hitzeman et al., *J. Biol. Chem.*, 255:2073 [1980]) or  
10 other glycolytic enzymes (Hess et al., *J. Adv. Enzyme Reg.* 7:149 [1968]; Holland et al., *Biochemistry*, 17:4900 [1978]), such as enolase, glyceraldehyde-3-phosphate dehydrogenase, hexokinase, pyruvate decarboxylase, phosphofructokinase, glucose-6-phosphate isomerase, 3-phosphoglycerate mutase, pyruvate kinase, triosephosphate isomerase, phosphoglucose isomerase, and glucokinase. In the  
15 construction of suitable expression plasmids, the termination sequences associated with these genes are also ligated into the expression vector 3' of the sequence desired to be expressed to provide polyadenylation of the mRNA and termination. Other promoters that have the additional advantage of transcription controlled by growth  
20 conditions are the promoter region for alcohol dehydrogenase 2, isocytochrome C, acid phosphatase, degradative enzymes associated with nitrogen metabolism, and the aforementioned glyceraldehyde-3-phosphate dehydrogenase, and enzymes responsible for maltose and galactose utilization. Any plasmid vector containing yeast-compatible promoter, origin of replication and termination sequences is suitable.

Cell cultures derived from multicellular organisms, such as plants, may be used  
25 as hosts to practice this invention. Transgenic plants can be obtained, for example, by transferring plasmids that encode 1-deoxyxylulose-5-phosphate synthase and a selectable marker gene, e.g., the kan gene encoding resistance to kanamycin, into *Agrobacterium tumifaciens* containing a helper Ti plasmid as described in Hoeckema et al., *Nature*, 303:179-181 [1983] and culturing the *Agrobacterium* cells  
30 with leaf slices, or other tissues or cells, of the plant to be transformed as described by An et al., *Plant Physiology*, 81:301-305 [1986]. Transformation of cultured plant host cells is normally accomplished through *Agrobacterium tumifaciens*. Cultures of mammalian host cells and other host cells that do not have rigid cell membrane  
35 barriers are usually transformed using the calcium phosphate method as originally described by Graham and Van der Eb (*Virology*, 52:546 [1978]) and modified as

described in sections 16.32-16.37 of Sambrook et al., *supra*. However, other methods for introducing DNA into cells such as Polybrene (Kawai and Nishizawa, *Mol. Cell. Biol.*, 4:1172 [1984]), protoplast fusion (Schaffner, *Proc. Natl. Acad. Sci. USA*, 77:2163 [1980]), electroporation (Neumann et al., *EMBO J.*, 1:841 [1982]), and direct microinjection into nuclei (Capecchi, *Cell*, 22:479 [1980]) may also be used. Additionally, animal transformation strategies are reviewed in Monastersky G.M. and Robl, J.M., *Strategies in Transgenic Animal Science*, ASM Press, Washington, D.C., 1995. Transformed plant calli may be selected through the selectable marker by growing the cells on a medium containing, e.g., kanamycin, and appropriate amounts of phytohormone such as naphthalene acetic acid and benzyladenine for callus and shoot induction. The plant cells may then be regenerated and the resulting plants transferred to soil using techniques well known to those skilled in the art.

In addition, a gene regulating 1-deoxyxylulose-5-phosphate synthase production can be incorporated into the plant along with a necessary promoter which is inducible. In the practice of this embodiment of the invention, a promoter that only responds to a specific external or internal stimulus is fused to the target cDNA. Thus, the gene will not be transcribed except in response to the specific stimulus. As long as the gene is not being transcribed, its gene product is not produced.

An illustrative example of a responsive promoter system that can be used in the practice of this invention is the glutathione-S-transferase (GST) system in maize. GSTs are a family of enzymes that can detoxify a number of hydrophobic electrophilic compounds that often are used as pre-emergent herbicides (Weigand et al., *Plant Molecular Biology*, 7:235-243 [1986]). Studies have shown that the GSTs are directly involved in causing this enhanced herbicide tolerance. This action is primarily mediated through a specific 1.1 kb mRNA transcription product. In short, maize has a naturally occurring quiescent gene already present that can respond to external stimuli and that can be induced to produce a gene product. This gene has previously been identified and cloned. Thus, in one embodiment of this invention, the promoter is removed from the GST responsive gene and attached to a 1-deoxyxylulose-5-phosphate synthase gene that previously has had its native promoter removed. This engineered gene is the combination of a promoter that responds to an external chemical stimulus and a gene responsible for successful production of 1-deoxyxylulose-5-phosphate synthase.

In addition to the methods described above, several methods are known in the art for transferring cloned DNA into a wide variety of plant species, including gymnosperms, angiosperms, monocots and dicots (see, e.g., Glick and Thompson, eds., *Methods in Plant Molecular Biology*, CRC Press, Boca Raton, Florida [1993], incorporated by reference herein). Representative examples include electroporation-facilitated DNA uptake by protoplasts in which an electrical pulse transiently permeabilizes cell membranes, permitting the uptake of a variety of biological molecules, including recombinant DNA (Rhodes et al., *Science*, **240**(4849):204-207 [1988]); treatment of protoplasts with polyethylene glycol (Lyznik et al., *Plant Molecular Biology*, **13**:151-161 [1989]); and bombardment of cells with DNA-laden microprojectiles which are propelled by explosive force or compressed gas to penetrate the cell wall (Klein et al., *Plant Physiol.* **91**:440-444 [1989] and Boynton et al., *Science*, **240**(4858):1534-1538 [1988]). Transformation of *Taxus* species can be achieved, for example, by employing the methods set forth in Han et al., *Plant Science*, **95**:187-196 (1994), incorporated by reference herein. A method that has been applied to Rye plants (*Secale cereale*) is to directly inject plasmid DNA, including a selectable marker gene, into developing floral tillers (de la Pena et al., *Nature* **325**:274-276 (1987)). Further, plant viruses can be used as vectors to transfer genes to plant cells. Examples of plant viruses that can be used as vectors to transform plants include the Cauliflower Mosaic Virus (Brisson et al., *Nature* **310**: 511-514 (1984); Additionally, plant transformation strategies and techniques are reviewed in Birch, R.G., *Ann Rev Plant Phys Plant Mol Biol*, **48**:297 (1997); Forester et al., *Exp. Agric.*, **33**:15-33 (1997). The aforementioned publications disclosing plant transformation techniques are incorporated herein by reference, and minor variations make these technologies applicable to a broad range of plant species.

Each of these techniques has advantages and disadvantages. In each of the techniques, DNA from a plasmid is genetically engineered such that it contains not only the gene of interest, but also selectable and screenable marker genes. A selectable marker gene is used to select only those cells that have integrated copies of the plasmid (the construction is such that the gene of interest and the selectable and screenable genes are transferred as a unit). The screenable gene provides another check for the successful culturing of only those cells carrying the genes of interest. A commonly used selectable marker gene is neomycin phosphotransferase II (NPT II). This gene conveys resistance to kanamycin, a compound that can be added directly to

the growth media on which the cells grow. Plant cells are normally susceptible to kanamycin and, as a result, die. The presence of the NPT II gene overcomes the effects of the kanamycin and each cell with this gene remains viable. Another selectable marker gene which can be employed in the practice of this invention is the gene which confers resistance to the herbicide glufosinate (Basta). A screenable gene commonly used is the  $\beta$ -glucuronidase gene (GUS). The presence of this gene is characterized using a histochemical reaction in which a sample of putatively transformed cells is treated with a GUS assay solution. After an appropriate incubation, the cells containing the GUS gene turn blue.

10 The plasmid containing one or more of these genes is introduced into either plant protoplasts or callus cells by any of the previously mentioned techniques. If the marker gene is a selectable gene, only those cells that have incorporated the DNA package survive under selection with the appropriate phytotoxic agent. Once the appropriate cells are identified and propagated, plants are regenerated. Progeny from  
15 the transformed plants must be tested to insure that the DNA package has been successfully integrated into the plant genome.

Mammalian host cells may also be used in the practice of the invention. Examples of suitable mammalian cell lines include monkey kidney CVI line transformed by SV40 (COS-7, ATCC CRL 1651); human embryonic kidney line 293S  
20 (Graham et al., *J. Gen. Virol.*, **36**:59 [1977]); baby hamster kidney cells (BHK, ATCC CCL 10); Chinese hamster ovary cells (Urlab and Chasin, *Proc. Natl. Acad. Sci USA* **77**:4216 [1980]); mouse sertoli cells (TM4, Mather, *Biol. Reprod.*, **23**:243 [1980]); monkey kidney cells (CVI-76, ATCC CCL 70); African green monkey kidney cells (VERO-76, ATCC CRL-1587); human cervical carcinoma cells (HELA,  
25 ATCC CCL 2); canine kidney cells (MDCK, ATCC CCL 34); buffalo rat liver cells (BRL 3A, ATCC CRL 1442); human lung cells (W138, ATCC CCL 75); human liver cells (Hep G2, HB 8065); mouse mammary tumor cells (MMT 060562, ATCC CCL 51); rat hepatoma cells (HTC, MI.54, Baumann et al., *J. Cell Biol.*, **85**:1 [1980]); and TRI cells (Mather et al., *Annals N.Y. Acad. Sci.*, **383**:44 [1982]).  
30 Expression vectors for these cells ordinarily include (if necessary) DNA sequences for an origin of replication, a promoter located in front of the gene to be expressed, a ribosome binding site, an RNA splice site, a polyadenylation site, and a transcription terminator site.

Promoters used in mammalian expression vectors are often of viral origin.  
35 These viral promoters are commonly derived from polyoma virus, Adenovirus 2, and

most frequently Simian Virus 40 (SV40). The SV40 virus contains two promoters that are termed the early and late promoters. These promoters are particularly useful because they are both easily obtained from the virus as one DNA fragment that also contains the viral origin of replication (Fiers et al., *Nature*, 273:113 [1978]). Smaller  
5 or larger SV40 DNA fragments may also be used, provided they contain the approximately 250-bp sequence extending from the HindIII site toward the BglII site located in the viral origin of replication.

Alternatively, promoters that are naturally associated with the foreign gene (homologous promoters) may be used provided that they are compatible with the host  
10 cell line selected for transformation.

An origin of replication may be obtained from an exogenous source, such as SV40 or other virus (e.g., Polyoma, Adeno, VSV, BPV) and inserted into the cloning vector. Alternatively, the origin of replication may be provided by the host cell chromosomal replication mechanism. If the vector containing the foreign gene is  
15 integrated into the host cell chromosome, the latter is often sufficient.

The use of a secondary DNA coding sequence can enhance production levels of 1-deoxyxylulose-5-phosphate synthase in transformed cell lines. The secondary coding sequence typically comprises the enzyme dihydrofolate reductase (DHFR). The wild-type form of DHFR is normally inhibited by the chemical methotrexate  
20 (MTX). The level of DHFR expression in a cell will vary depending on the amount of MTX added to the cultured host cells. An additional feature of DHFR that makes it particularly useful as a secondary sequence is that it can be used as a selection marker to identify transformed cells. Two forms of DHFR are available for use as secondary sequences, wild-type DHFR and MTX-resistant DHFR. The type of DHFR used in a  
25 particular host cell depends on whether the host cell is DHFR deficient (such that it either produces very low levels of DHFR endogenously, or it does not produce functional DHFR at all). DHFR-deficient cell lines such as the CHO cell line described by Urlaub and Chasin, *supra*, are transformed with wild-type DHFR coding sequences. After transformation, these DHFR-deficient cell lines express functional  
30 DHFR and are capable of growing in a culture medium lacking the nutrients hypoxanthine, glycine and thymidine. Nontransformed cells will not survive in this medium.

The MTX-resistant form of DHFR can be used as a means of selecting for transformed host cells in those host cells that endogenously produce normal amounts  
35 of functional DHFR that is MTX sensitive. The CHO-K1 cell line (ATCC No. CL 61)

possesses these characteristics, and is thus a useful cell line for this purpose. The addition of MTX to the cell culture medium will permit only those cells transformed with the DNA encoding the MTX-resistant DHFR to grow. The nontransformed cells will be unable to survive in this medium.

5 Prokaryotes may also be used as host cells for the initial cloning steps of this invention. They are particularly useful for rapid production of large amounts of DNA, for production of single-stranded DNA templates used for site-directed mutagenesis, for screening many mutants simultaneously, and for DNA sequencing of the mutants generated. Suitable prokaryotic host cells include *E. coli* K12 strain 94 (ATCC  
10 No. 31,446), *E. coli* strain W3110 (ATCC No. 27,325) *E. coli* X1776 (ATCC No. 31,537), and *E. coli* B; however many other strains of *E. coli*, such as HB101, JM101, NM522, NM538, NM539, and many other species and genera of prokaryotes including bacilli such as *Bacillus subtilis*, other enterobacteriaceae such as *Salmonella typhimurium* or *Serratia marcesans*, and various *Pseudomonas* species may all be  
15 used as hosts. Prokaryotic host cells or other host cells with rigid cell walls are preferably transformed using the calcium chloride method as described in section 1.82 of Sambrook et al., *supra*. Alternatively, electroporation may be used for transformation of these cells. Prokaryote transformation techniques are set forth in Dower, W.J., in Genetic Engineering, Principles and Methods, 12:275-296, Plenum  
20 Publishing Corp., 1990; Hanahan et al., *Meth. Enzymol.*, 204:63 (1991).

As a representative example, cDNA sequences encoding 1-deoxyxylulose-5-phosphate synthase may be transferred to the (His)<sub>6</sub>-Tag pET vector commercially available (from Novagen) for overexpression in *E. coli* as heterologous host. This pET expression plasmid has several advantages in high level heterologous expression  
25 systems. The desired cDNA insert is ligated in frame to plasmid vector sequences encoding six histidines followed by a highly specific protease recognition site (thrombin) that are joined to the amino terminus codon of the target protein. The histidine "block" of the expressed fusion protein promotes very tight binding to immobilized metal ions and permits rapid purification of the recombinant protein by  
30 immobilized metal ion affinity chromatography. The histidine leader sequence is then cleaved at the specific proteolysis site by treatment of the purified protein with thrombin, and the 1-deoxyxylulose-5-phosphate synthase again purified by immobilized metal ion affinity chromatography, this time using a shallower imidazole gradient to elute the recombinant synthases while leaving the histidine block still  
35 adsorbed. This overexpression-purification system has high capacity, excellent



resolving power and is fast, and the chance of a contaminating *E. coli* protein exhibiting similar binding behavior (before and after thrombin proteolysis) is extremely small.

As will be apparent to those skilled in the art, any plasmid vectors containing  
5 replicon and control sequences that are derived from species compatible with the host cell may also be used in the practice of the invention. The vector usually has a replication site, marker genes that provide phenotypic selection in transformed cells, one or more promoters, and a polylinker region containing several restriction sites for insertion of foreign DNA. Plasmids typically used for transformation of *E. coli*  
10 include pBR322, pUC18, pUC19, pUCI18, pUC119, and Bluescript M13, all of which are described in sections 1.12-1.20 of Sambrook et al., *supra*. However, many other suitable vectors are available as well. These vectors contain genes coding for ampicillin and/or tetracycline resistance which enables cells transformed with these vectors to grow in the presence of these antibiotics.

15 The promoters most commonly used in prokaryotic vectors include the  $\beta$ -lactamase (penicillinase) and lactose promoter systems (Chang et al. *Nature*, 375:615 [1978]; Itakura et al., *Science*, 198:1056 [1977]; Goeddel et al., *Nature*, 281:544 [1979]) and a tryptophan (trp) promoter system (Goeddel et al., *Nucl. Acids Res.*, 8:4057 [1980]; EPO Appl. Publ. No. 36,776), and the alkaline phosphatase  
20 systems. While these are the most commonly used, other microbial promoters have been utilized, and details concerning their nucleotide sequences have been published, enabling a skilled worker to ligate them functionally into plasmid vectors (see Siebenlist et al., *Cell*, 20:269 [1980]).

Many eukaryotic proteins normally secreted from the cell contain an  
25 endogenous secretion signal sequence as part of the amino acid sequence. Thus, proteins normally found in the cytoplasm can be targeted for secretion by linking a signal sequence to the protein. This is readily accomplished by ligating DNA encoding a signal sequence to the 5' end of the DNA encoding the protein and then expressing this fusion protein in an appropriate host cell. The DNA encoding the  
30 signal sequence may be obtained as a restriction fragment from any gene encoding a protein with a signal sequence. Thus, prokaryotic, yeast, and eukaryotic signal sequences may be used herein, depending on the type of host cell utilized to practice the invention. The DNA and amino acid sequence encoding the signal sequence portion of several eukaryotic genes including, for example, human growth hormone,  
35 proinsulin, and proalbumin are known (see Stryer, *Biochemistry* W.H. Freeman and

Company, New York, NY, p. 769 [1988]), and can be used as signal sequences in appropriate eukaryotic host cells. Yeast signal sequences, as for example acid phosphatase (Arima et al., *Nuc. Acids Res.*, 11:1657 [1983]),  $\alpha$ -factor, alkaline phosphatase and invertase may be used to direct secretion from yeast host cells.

5 Prokaryotic signal sequences from genes encoding, for example, LamB or OmpF (Wong et al., *Gene*, 68:193 [1988]), MalE, PhoA, or beta-lactamase, as well as other genes, may be used to target proteins from prokaryotic cells into the culture medium.

Trafficking sequences from plants, animals and microbes can be employed in the practice of the invention to direct the 1-deoxyxylulose-5-phosphate synthase proteins of the present invention to the cytoplasm, endoplasmic reticulum, mitochondria or other cellular components, or to target the protein for export to the medium. These considerations apply to the overexpression of 1-deoxyxylulose-5-phosphate synthase, and to direction of expression within cells or intact organisms to permit gene product function in any desired location.

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15 The construction of suitable vectors containing DNA encoding replication sequences, regulatory sequences, phenotypic selection genes and the 1-deoxyxylulose-5-phosphate synthase DNA of interest are prepared using standard recombinant DNA procedures. Isolated plasmids and DNA fragments are cleaved, tailored, and ligated together in a specific order to generate the desired vectors, as is well known in the art (see, for example, Sambrook et al., *supra*).

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As discussed above, 1-deoxyxylulose-5-phosphate synthase variants are preferably produced by means of mutation(s) that are generated using the method of site-specific mutagenesis. This method requires the synthesis and use of specific oligonucleotides that encode both the sequence of the desired mutation and a sufficient number of adjacent nucleotides to allow the oligonucleotide to stably hybridize to the DNA template.

25

The foregoing may be more fully understood in connection with the following representative examples, in which "Plasmids" are designated by a lower case p followed by an alphanumeric designation. The starting plasmids used in this invention are either commercially available, publicly available on an unrestricted basis, or can be constructed from such available plasmids using published procedures. In addition, other equivalent plasmids are known in the art and will be apparent to the ordinary artisan.

30

"Digestion", "cutting" or "cleaving" of DNA refers to catalytic cleavage of the DNA with an enzyme that acts only at particular locations in the DNA. These

35

enzymes are called restriction endonucleases, and the site along the DNA sequence where each enzyme cleaves is called a restriction site. The restriction enzymes used in this invention are commercially available and are used according to the instructions supplied by the manufacturers. (See also sections 1.60-1.61 and sections 3.38-3.39 of Sambrook et al., *supra*.)

"Recovery" or "isolation" of a given fragment of DNA from a restriction digest means separation of the resulting DNA fragment on a polyacrylamide or an agarose gel by electrophoresis, identification of the fragment of interest by comparison of its mobility versus that of marker DNA fragments of known molecular weight, removal of the gel section containing the desired fragment, and separation of the gel from DNA. This procedure is known generally. For example, see Lawn et al. (*Nucleic Acids Res.*, 9:6103-6114 [1982]), and Goeddel et al. (*Nucleic Acids Res.*, *supra*).

These and other aspects of the present invention may be made more apparent in connection with the following representative examples that are presented for purposes of illustrating some of the inventive concepts.

#### EXAMPLE 1

##### cDNA Library Construction and Screening

**cDNA Library Construction and Screening.** Peppermint (*Mentha x piperita*) leaf secretory cells are highly specialized for isoprenoid (monoterpene essential oil) formation and, thus, a highly enriched source of mRNA species encoding proteins involved in essential oil biosynthesis. Consequently, total RNA was extracted (Logemann, J. et al., *Anal. Biochem.* 163:16-20 (1987)) from secretory cells which had been isolated from 5-day-old peppermint leaves (Gershenzon, J. et al., *Anal. Biochem.* 200:130-138 (1992)). Poly(A)<sup>+</sup>-RNA was purified by chromatography on oligo(dT)-cellulose (Pharmacia), and 5 µg of the resulting mRNA was utilized to construct a λZAP cDNA library according to the manufacturer's instructions (Stratagene). One hundred and fifty randomly picked and purified clones were *in vivo*-excised and the resulting phagemids were sequenced using T3 and T7 primers. In addition to several genes of known function in isoprenoid biosynthesis, two clones (designated pDS1 and pDS2) were identified which exhibited significant sequence similarity to a recently described *Arabidopsis thaliana* transketolase gene (*CLAI*) of unknown function, the disruption of which results in an albino mutant arrested in chloroplast development (Mandel, M.A. et al., *Plant J.* 9:649-658 (1996)). The nucleotide sequence of the cDNA insert of pDS1 is

set forth in SEQ ID NO:1, and the nucleotide sequence of the cDNA insert of pDS2 is set forth in SEQ ID NO:2.

A set of 3,000 plaques was then screened with a nucleic acid probe (SEQ ID NO:9) derived by PCR from the pDS1 cDNA insert (SEQ ID NO:1). This procedure  
5 afforded 47 positive signals under high-stringency hybridization conditions. After one additional cycle of hybridization, the positive clones were *in vivo*-excised, the insert sizes were determined by PCR, and the 20 largest clones were partially sequenced. Three of these clones (designated pDS16, pDS29 and pDS39) appeared to be of full-length and were entirely sequenced on both strands. The nucleotide sequence of the  
10 cDNA insert of pDS16 is set forth in SEQ ID NO:3, the nucleotide sequence of the cDNA insert of pDS29 is set forth in SEQ ID NO:5 and the nucleotide sequence of the cDNA insert of pDS39 is set forth in SEQ ID NO:7.

**Structure of cDNA Insert of DXPS Clone pDS29 (SEQ ID NO:5).** The cDNA insert of *DXPS* clone pDS29 (SEQ ID NO:5), which yielded the highest  
15 expressed level of synthase activity, contains an open reading frame (ORF) of 2172 nucleotides. The first 70 deduced amino acid residues show the general characteristics of plastidial targeting sequences (von Heijne, G. et al., *Eur. J. Biochem.* 180:535-545 (1989)), consistent with the proposed subcellular location of the enzyme in plant cells. By excluding the putative transit peptide residues, the  
20 sequence corresponds to a mature protein of about 650 amino acids, with a predicted size of roughly 71 kDa. This compares to a deduced protein of 620 residues with a predicted size of 67.6 kDa described by Boronat and associates in a preliminary report on a *DXPS* clone from *E. coli* (Lois, L.M. et al., Third Terpnnet Meeting of the European Network on Plant Isoprenoids, Poitiers, France, May 29-30 (1997)). An  
25 alignment of translated transketolase sequences (devoid of plastid-targeting peptides where appropriate) shows very high similarity/identity values between the peppermint *DXPS* and *CLA1* from *Arabidopsis* (Mandel, M.A. et al., *Plant J.* 9:649-658 (1996)) (85/77 %), *ORF 2814* (part of the *puf* operon in the photosynthetic gene cluster) from the purple non-sulfur photosynthetic bacterium *Rhodobacter capsulata* (Youvan,  
30 D.C. et al., *Cell* 37:949-957 (1984)) (72/56 %), *ORF f620* (map position 9.43 min, the presumptive *DXPS* of *E. coli* (Lois, L.M. et al., Third Terpnnet Meeting of the European Network on Plant Isoprenoids, Poitiers, France, May 29-30 (1997))); 69/48 %), and a deduced protein from the cyanobacterium *Synechocystis* sp. strain PCC6803 (Kaneko, T. et al., *DNA Res.* 3:109-136 (1996)) (65/45 %) (FIGURE 4).  
35 These conserved sequences appear to form a new class of transketolases that is

distinct from the well-characterized transketolases involved in the pentose phosphate pathway (FIGURE 4), and the extensive sequence similarity among these genes of diverse origin suggests that they all encode *DXPS* or a very closely related synthase. In addition, the general transketolase consensus TPP-binding motif  
 5 (GDG(X)<sub>7-8</sub>E(X)<sub>3-4</sub>A(X)<sub>11-13</sub>NN)(SEQ ID NO:10) determined by Hawkins et al. (Hawkins, C.F. et al., *FEBS Lett.* **255**:77-82 (1989)) was observed in this new transketolase type as:

DG(A/S)(X)T(A/G)G(Q/M)AXEAXN(N/H)AG(X)<sub>7</sub>.

<sub>8</sub>(I/V)(V/T)LNDN (SEQ ID NO:11)(residues 219-250 of the peppermint sequence).

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## EXAMPLE 2

### cDNA Expression in *E. coli* and Product Identification

The cDNA inserts of clones pDS16 (SEQ ID NO:3), pDS29 (SEQ ID NO:5), and pDS39 (SEQ ID NO:7) were evaluated by heterologous expression for an enzyme capable of catalyzing the condensation reaction of pyruvate and GAP to a  
 15 deoxypentulose phosphate (FIGURE 1).

*E. coli* SOLR cells harboring pDS16, pDS29 or pDS39 were grown at 37°C in 5 ml of LB medium supplemented with appropriate antibiotics to an OD<sub>600</sub> of 0.7, transferred to a new flask containing 50 ml of the same medium, and incubated at 20°C for 2 h. After induction with 200 µmol isopropyl-1-thio-β-D-galactopyranoside  
 20 (IPTG), the cells were maintained for another 14 h at 20°C. Bacteria were harvested by centrifugation (1800 x g, 10 min), washed with 5 ml of assay buffer (100 mM sodium phosphate (pH 6.5) containing 3 mM MgCl<sub>2</sub>, 0.1 mM EDTA, 5 mM NaF, 20 µM phenylmethanesulfonyl fluoride, and 100 µM thiamin diphosphate), and then resuspended in 1 ml of assay buffer. Cells were disrupted by brief sonication at  
 25 0-4°C, and the resulting homogenate was centrifuged as above to pellet debris. An aliquot (50 µl) of the supernatant was transferred to a 600 µl Eppendorf tube, to which 30 µM [2-<sup>14</sup>C] pyruvate (18.5 kBq) and 0.4 µM *D,L*-glyceraldehyde-3-phosphate (GAP) (or 0.4 µM *D*-GAP) were added, and the mixture was incubated at  
 30 23°C for 30 min. The reaction was terminated by addition of 70 µl acetone and freezing at -20°C for 20 min. Following centrifugation (14,000 rpm, bench-top centrifuge) to remove denatured protein, the supernatant was transferred to a new vial and evaporated to dryness. The residue was dissolved in 40 µl H<sub>2</sub>O and analyzed by reversed-phase (C<sub>18</sub>) ion-pair radio-HPLC using a procedure previously described with minor modifications (McCaskill, D. & Croteau, R., *Anal. Biochem.* **215**:142-149  
 35 (1993)).

Enzyme assays performed with extracts of IPTG-induced cells harboring plasmid pDS29, including the cDNA sequence set forth in SEQ ID NO:5, or pDS39, including the cDNA sequence set forth in SEQ ID NO:7, showed the GAP-dependent appearance of a labeled product with  $R_t$  of 35.5 min that was formed in significantly higher amounts than in control assays (extracts from cells containing vector without insert). The radio-labeled product was isolated by semi-preparative HPLC and hydrolyzed with excess acid phosphatase, and the resulting sugar was lyophilized and silylated (100  $\mu$ l bis(trimethylsilyl)trifluoroacetamide, 10  $\mu$ l pyridine and 100  $\mu$ g  $\text{Na}_2\text{SO}_4$ ; 80°C for 1 h). GC-MS analysis (of the silylated biosynthetic product and of silylated authentic 1-deoxy-*D*-xylulose) was performed using a Hewlett-Packard 5840A/5985B system equipped with a 30 m x 0.25 mm diameter fused silica column coated with a 0.25  $\mu$ m film of HP 5MS (Hewlett-Packard). The oven was programmed from 90°C (2 min hold) at 20°C/min to 250°C (2 min hold), then at 20°C/min to 300°C at 10 psi He, and EI spectra were recorded at 70 eV with an electron multiplier voltage of 2200 V. Full spectra were acquired and selected diagnostic ions were monitored:  $m/z$  307 [ $\text{M}^+ - 43 (\text{CH}_3\text{CO})$ ];  $m/z$  277 [ $\text{M}^+ - 73 ((\text{CH}_3)_3\text{Si})$ ];  $m/z$  218 [ $\text{M}^+ - 43 (\text{CH}_3\text{CO}) - 89 ((\text{CH}_3)_3\text{SiO})$ ];  $m/z$  205 [ $\text{M}^+ - 145 (\text{CH}_3\text{COCHOSi}(\text{CH}_3)_3)$ ];  $m/z$  204 [ $((\text{CH}_3)_3\text{SiOCHCH}_2\text{OSi}(\text{CH}_3)_3)^+$ ];  $m/z$  147 [ $((\text{CH}_3)_2\text{SiOSi}(\text{CH}_3)_3)^+$ ];  $m/z$  132 [ $(\text{Si}(\text{CH}_3)_3\text{OCH}_2\text{CHO})^+$ ];  $m/z$  117 [ $((\text{CH}_3)_3\text{SiOCH}_2\text{CH}_2)^+$ ];  $m/z$  103 [ $((\text{CH}_3)_3\text{SiOCH}_2)^+$ ];  $m/z$  89 [ $((\text{CH}_3)_3\text{SiO})^+$ ];  $m/z$  73 [ $((\text{CH}_3)_3\text{Si})^+$ ]. The silylated derivative of the biosynthetic product eluted at an  $R_t$  of 6.71 min; the silylated derivative of authentic 1-deoxy-*D*-xylulose eluted at an  $R_t$  of 6.70 min.

In accordance with the detailed procedures set forth in the preceding paragraphs, *E. coli* cultures transfected with phagemids derived from pDS16, including the cDNA sequence set forth in SEQ ID NO:3, pDS29, including the cDNA sequence set forth in SEQ ID NO:5, and pDS39, including the cDNA sequence set forth in SEQ ID NO:7, were each induced with isopropyl-1 thio- $\beta$ -*D*-galactopyranoside (IPTG), the corresponding bacterial cells were harvested and homogenized, and the extracts were assayed using [2- $^{14}\text{C}$ ] pyruvate and *D,L*-glyceraldehyde-3 phosphate as co-substrates. Preparations from *E. coli* cells transfected with pDS29, including the cDNA sequence set forth in SEQ ID NO:5, and pDS39, including the cDNA sequence set forth in SEQ ID NO:7, yielded a prominent new radioactive component in the reaction mixture that upon reversed-phase ion-pair radio-HPLC exhibited a  $R_t$  (35.5 min) consistent with that of a sugar (pentulose)

phosphate (McCaskill, D. & Croteau, R., *Anal. Biochem.* **215**:142-149 (1993)). The same enzymatic product was generated with *D*-glyceraldehyde-3-phosphate as co-substrate, indicating that the *D*-antipode is the likely natural substrate of the functionally expressed transketolase. The presumptive pentulose phosphate product from preparative enzyme incubations (*E. coli* transformed with pDS29, including the cDNA sequence set forth in SEQ ID NO:5) was purified by HPLC and hydrolyzed with acid phosphatase, and the resulting sugar was silylated. This derivatized product of the recombinant enzyme was then analyzed by combined capillary GC-MS and shown to possess the identical retention time ( $6.71 \pm 0.03$  min) and mass spectrum as that of an authentic sample of silylated 1-deoxy-*D*-xylulose (FIGURES 2A and 2B). The combined evidence thus indicated that a cDNA encoding 1-deoxyxylulose-5-phosphate synthase (*DXPS*) had been acquired. *DXPS* activity was significantly higher in the IPTG-induced *E. coli* cells expressing pDS29, including the cDNA sequence set forth in SEQ ID NO:5, when compared to identically treated cells containing the same plasmid devoid of cDNA insert (SEQ ID NO:5) (7-fold higher than endogenous activity,  $n = 7$ ,  $p < 0.01$ ).

### EXAMPLE 3

#### RNA Blot Analysis and Determination of Monoterpene Biosynthetic Rate

Peppermint oil gland secretory cell RNA was isolated from leaves of different ages, separated on a 1.5 % formaldehyde-agarose gel (5  $\mu$ g each lane), and blotted onto Nylon membranes. *DXPS* mRNA was detected with a  $^{32}$ P-labeled probe (SEQ ID NO:12) prepared from cDNA clone pDS29 cDNA insert (SEQ ID NO:5). Administration of  $^{14}$ CO<sub>2</sub> to peppermint plants and the isolation and quantification of the leaf monoterpenes produced were performed as described previously (Gershenzon, J. et al., *Oecologia* **96**:583-592 (1993)).

RNA blot analyses showed a direct correlation between steady-state levels of the *DXPS* message and monoterpene production, as determined by (Gershenzon, J. et al., *Anal. Biochem.* **200**:130-138 (1992)) CO<sub>2</sub> incorporation, thus suggesting activation of the non-mevalonate pathway to supply the IPP precursor for subsequent monoterpene biosynthesis in peppermint oil glands (FIGURE 3).

The cloning, characterization and expression of *DXPS* from peppermint provides direct evidence for the operation of the mevalonate-independent pathway in plants, where, in parallel with the classical cytosolic mevalonate pathway for sterol biosynthesis (Lichtenthaler, H.K. et al., *FEBS Lett.* **400**:271-274 (1997)), this plastidial pyruvate/GAP pathway functions to synthesize a very broad range of

isoprenoids (Lichtenthaler, H.K. et al., *FEBS Lett.* 400:271-274 (1997)); (Zeidler J.G. et al., *Z. Naturforsch.* 52c:15-23 (1997)); (Eisenreich, W. et al., *Tetrahedron Lett.* 38:3889-3892 (1997)); (Eisenreich, W. et al., *Proc. Natl. Acad. Sci. USA* 93:6431-6436 (1996)); and (Schwarz, M.K., PhD thesis, ETH, Zurich, Switzerland (1994)).

The novel transketolases of the present invention are highly conserved between bacteria and plants, but absent in animals which rely entirely on the classical mevalonate pathway for isoprenoid biosynthesis. The novel transketolases of the present invention are targeted to the plastids of plant cells, in which the new pathway operates, suggesting that plants have maintained the "bacterial" isoprenoid biosynthetic pathway from the prokaryotic endosymbiont that gave rise to this eukaryotic organelle.

The new pathway, termed the pyruvate/glyceraldehyde-3-phosphate pathway for which the initial steps have only recently been proposed, has been overlooked in the past in spite of the fact that, in plants and certain bacteria, it is quantitatively and functionally of greater significance than the classical mevalonate pathway. Thus, all plastid-derived isoprenoids of plants are formed by this route which yields a wide variety of structures with numerous functions in growth, development and defense.

#### EXAMPLE 4

##### Hybridization Conditions

RNA samples from the following plant species were separated on a 1.5% agarose gel containing 6% formaldehyde: *Pinus taeda* (1 µg messenger RNA isolated from wounded stem); *Pinus taeda* (20 µg total RNA isolated from wounded stem); *Pseudotsuga menziesii* (2 µg total RNA isolated from wounded stem); *Abies grandis* (20 µg total RNA isolated from wounded stem); *Taxus canadensis* (20 µg total RNA isolated from needles); *Taxus cuspidata* (20 µg total RNA isolated from needles); *Oryza sativa* (20 µg total RNA isolated from 20 day old developing seeds); *Triticum aestivum* (20 µg total RNA isolated from leaves); *Lycopersicon esculentum* (20 µg total RNA isolated from leaves); *Hyoscyamus niger* (20 µg total RNA isolated from leaves); *Citrus limon* (20 µg total RNA isolated from leaves); *Mentha spicata* (10 µg total RNA isolated from glandular trichomes); *Salvia officinales* (20 µg total RNA isolated from leaves); *Coleus blumei* (20 µg total RNA isolated from leaves).



The gel containing the separated RNA samples was blotted onto Hybond N<sup>+</sup> Nylon membrane (Amersham) and was prehybridized for one hour at 42°C. The nucleic acid sequence set forth in SEQ ID NO:5 was used as a template for generating a <sup>32</sup>P-labelled hybridization probe. Hybridization was carried out at 42°C for ten  
5 hours. The composition of the hybridization and prehybridization buffer was: 30% formamide, 5 X Denhardt's reagent, 0.1% sodium dodecyl sulfate, 5 X SSPE. The composition of 1 liter of a 50 X stock solution of Denhardt's reagent is: 5g ficoll, 5g polyvinyl pyrrolidone and 5g bovine serum albumin. The composition of 1 liter of a 10  
10 X stock solution of SSPE is 87.7g sodium chloride, 13.8g NaH<sub>2</sub>PO<sub>4</sub>H<sub>2</sub>O, 3.7g EDTA at pH7.4. The blot was washed in 6 X SSC for ten minutes at 42°C. Autoradiography revealed that the hybridization probe recognized the corresponding mRNA species encoding a 1-deoxyxylulose-5-phosphate synthase from each sample of plant mRNA.

High stringency was conditions under which the foregoing probe derived from  
15 the nucleic acid sequence set forth in SEQ ID NO:5 will remain hybridized to Northern blotted mRNA species encoding 1-deoxyxylulose-5-phosphate synthase proteins of the present invention, or to Southern blotted DNA species encoding 1-deoxyxylulose-5-phosphate synthase proteins of the present invention are: two, fifteen minute washes in 2 X SSC at room temperature (18°C to 25°C), followed by  
20 two, twenty minute washes in 0.2 X SSC at 65°C).

While the preferred embodiment of the invention has been illustrated and described, it will be appreciated that various changes can be made therein without departing from the spirit and scope of the invention.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. An isolated nucleic acid molecule encoding at least a functional portion of a 1-deoxyxylulose-5-phosphate synthase from an essential oil plant.
2. An isolated nucleic acid molecule of Claim 1 encoding at least a functional portion of a 1-deoxyxylulose-5-phosphate synthase from a species from the family Lamiaceae.
3. An isolated nucleic acid molecule of Claim 2 encoding at least a functional portion of a 1-deoxyxylulose-5-phosphate synthase from a species from the genus *Mentha*.
4. An isolated nucleic acid molecule of Claim 3 encoding at least a functional portion of a *Mentha piperita* 1-deoxyxylulose-5-phosphate synthase.
5. An isolated nucleic acid molecule of Claim 1 having a nucleotide sequence selected from the group consisting of SEQ ID NO:3, SEQ ID NO:5 and SEQ ID NO:7.
6. An isolated nucleic acid molecule of Claim 1 which encodes an amino acid sequence selected from the group consisting of SEQ ID NO:4, SEQ ID NO:6 and SEQ ID NO:8.
7. An isolated nucleic acid molecule, encoding at least a portion of a 1-deoxyxylulose-5-phosphate synthase protein, from an essential oil plant, that hybridizes to the complementary strand of the nucleic acid sequence set forth in SEQ ID NO:3 under the Northern blot hybridization conditions set forth in Example 4, said isolated nucleic acid molecule being capable of remaining hybridized to the complementary strand of the nucleic acid sequence set forth in SEQ ID NO:3 under the stringent Northern blot wash conditions set forth in Example 4.
8. An isolated, recombinant 1-deoxyxylulose-5-phosphate synthase protein from a plant species.

9. An isolated, recombinant 1-deoxyxylulose-5-phosphate synthase protein of Claim 8, said protein being from an essential oil plant species.

10. An isolated, recombinant 1-deoxyxylulose-5-phosphate synthase protein of Claim 8, said protein being from the genus *Mentha*.

11. An isolated, recombinant 1-deoxyxylulose-5-phosphate synthase protein of Claim 8, said protein being from *Mentha piperita*.

12. An isolated, recombinant 1-deoxyxylulose-5-phosphate synthase protein of Claim 8, said protein having the amino acid sequence of a protein selected from the group consisting of SEQ ID NO:4, SEQ ID NO:6 and SEQ ID NO:8.

13. A replicable expression vector comprising a nucleic acid sequence of any one of Claim 1, Claim 2, Claim 3, Claim 4, Claim 5, Claim 6 and Claim 7.

14. A host cell comprising a vector of Claim 13.

15. A host cell of Claim 14 wherein said host cell is a plant cell.

16. A method of altering 1-deoxyxylulose-5-phosphate synthase activity in a suitable host cell comprising introducing into said host cell an expression vector of Claim 13 under conditions enabling expression of a 1-deoxyxylulose-5-phosphate synthase protein, or a functional portion thereof, encoded by said vector.

17. The method of Claim 16 wherein said host cell is a plant cell.

18. A method of reducing 1-deoxyxylulose-5-phosphate synthase activity in a suitable host cell comprising introducing into said host cell a vector comprising a nucleic acid sequence of any one of Claim 1, Claim 2, Claim 3, Claim 4, Claim 5, Claim 6 and Claim 7, said nucleic acid sequence being in antisense orientation relative to a promoter sequence that controls the transcription of said nucleic acid sequence.

**AMENDED CLAIMS**

[received by the International Bureau on 9 February 1999 (09.02.99);  
original claims 1-4, 7 and 16 amended; remaining claims unchanged (2 pages)]

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. An isolated nucleic acid molecule encoding a 1-deoxyxylulose-5-phosphate synthase from an essential oil plant.

2. An isolated nucleic acid molecule of Claim 1 encoding a 1-deoxyxylulose-5-phosphate synthase from a species from the family Lamiaceae.

3. An isolated nucleic acid molecule of Claim 2 encoding a 1-deoxyxylulose-5-phosphate synthase from a species from the genus *Mentha*.

4. An isolated nucleic acid molecule of Claim 3 encoding a *Mentha piperita* 1-deoxyxylulose-5-phosphate synthase.

5. An isolated nucleic acid molecule of Claim 1 having a nucleotide sequence selected from the group consisting of SEQ ID NO:3, SEQ ID NO:5 and SEQ ID NO:7.

6. An isolated nucleic acid molecule of Claim 1 which encodes an amino acid sequence selected from the group consisting of SEQ ID NO:4, SEQ ID NO:6 and SEQ ID NO:8.

7. An isolated nucleic acid molecule, encoding a 1-deoxyxylulose-5-phosphate synthase protein, from an essential oil plant, that hybridizes to the complementary strand of the nucleic acid sequence set forth in SEQ ID NO:3 under the Northern blot hybridization conditions set forth in Example 4, said isolated nucleic acid molecule being capable of remaining hybridized to the complementary strand of the nucleic acid sequence set forth in SEQ ID NO:3 under the stringent Northern blot wash conditions set forth in Example 4.

8. An isolated, recombinant 1-deoxyxylulose-5-phosphate synthase protein from a plant species.

9. An isolated, recombinant 1-deoxyxylulose-5-phosphate synthase protein of Claim 8, said protein being from an essential oil plant species.

10. An isolated, recombinant 1-deoxyxylulose-5-phosphate synthase protein of Claim 8, said protein being from the genus *Mentha*.

11. An isolated, recombinant 1-deoxyxylulose-5-phosphate synthase protein of Claim 8, said protein being from *Mentha piperita*.

12. An isolated, recombinant 1-deoxyxylulose-5-phosphate synthase protein of Claim 8, said protein having the amino acid sequence of a protein selected from the group consisting of SEQ ID NO:4, SEQ ID NO:6 and SEQ ID NO:8.

13. A replicable expression vector comprising a nucleic acid sequence of any one of Claim 1, Claim 2, Claim 3, Claim 4, Claim 5, Claim 6 and Claim 7.

14. A host cell comprising a vector of Claim 13.

15. A host cell of Claim 14 wherein said host cell is a plant cell.

16. A method of altering 1-deoxyxylulose-5-phosphate synthase activity in a suitable host cell comprising introducing into said host cell an expression vector of Claim 13 under conditions enabling expression of a 1-deoxyxylulose-5-phosphate synthase protein encoded by said vector.

17. The method of Claim 16 wherein said host cell is a plant cell.

18. A method of reducing 1-deoxyxylulose-5-phosphate synthase activity in a suitable host cell comprising introducing into said host cell a vector comprising a nucleic acid sequence of any one of Claim 1, Claim 2, Claim 3, Claim 4, Claim 5, Claim 6 and Claim 7, said nucleic acid sequence being in antisense orientation relative to a promoter sequence that controls the transcription of said nucleic acid sequence.

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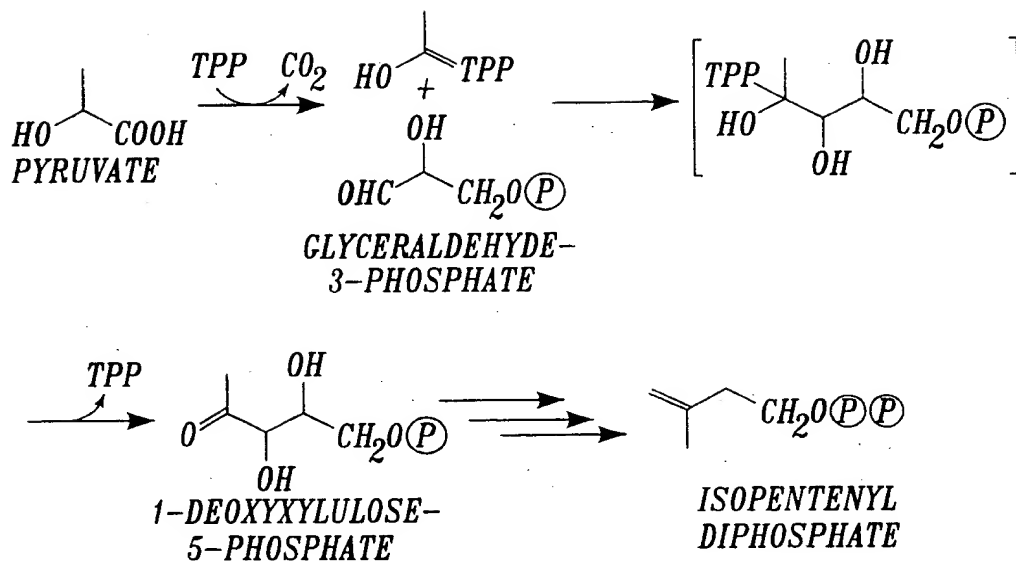
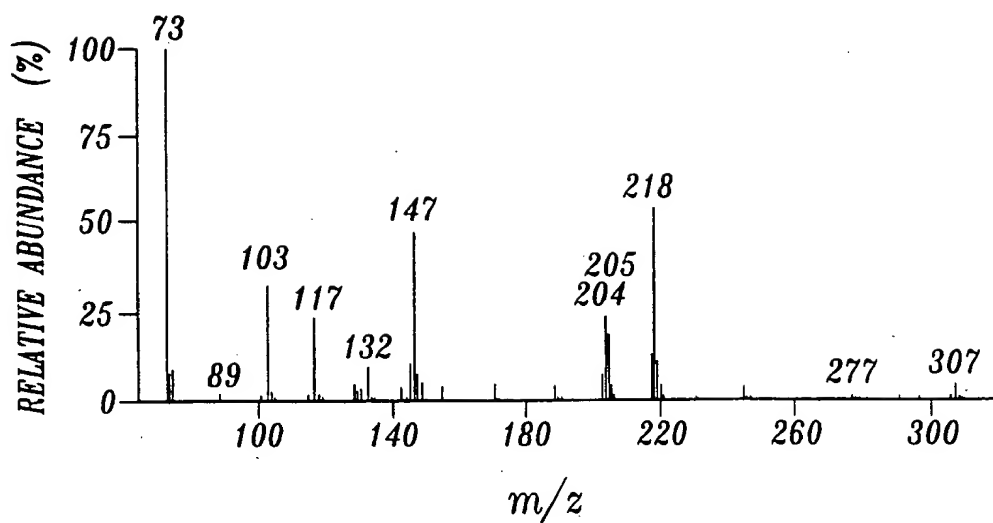
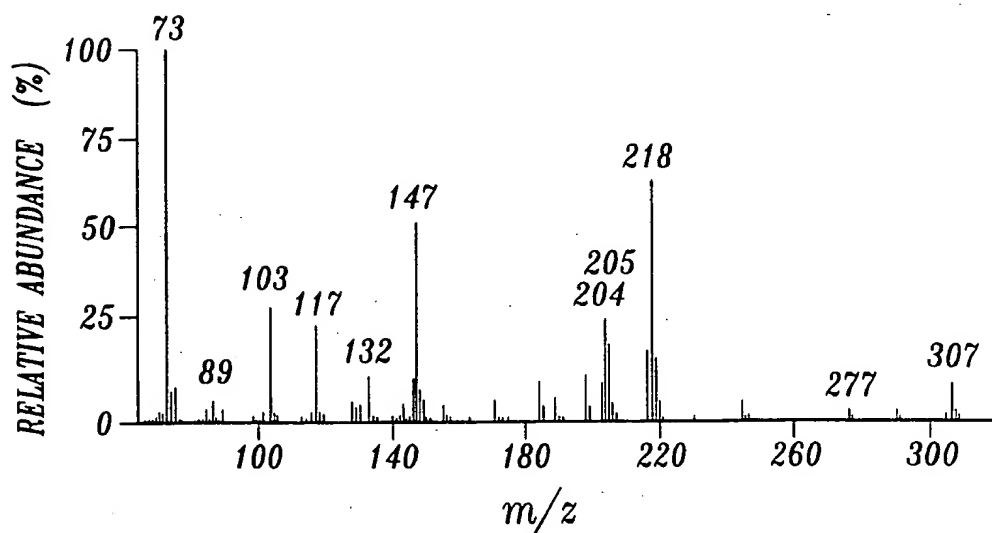
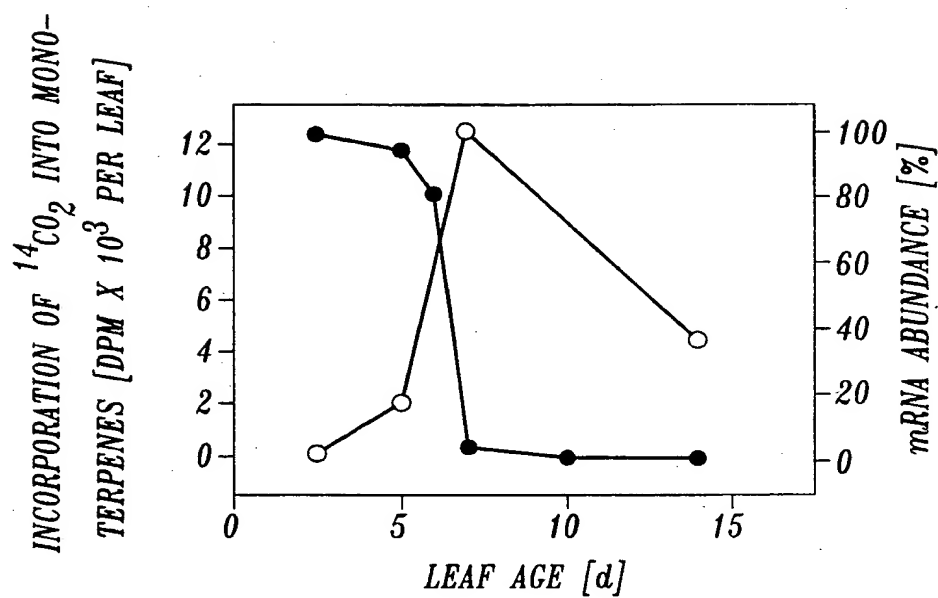


Fig. 1

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*Fig. 2A**Fig. 2B*

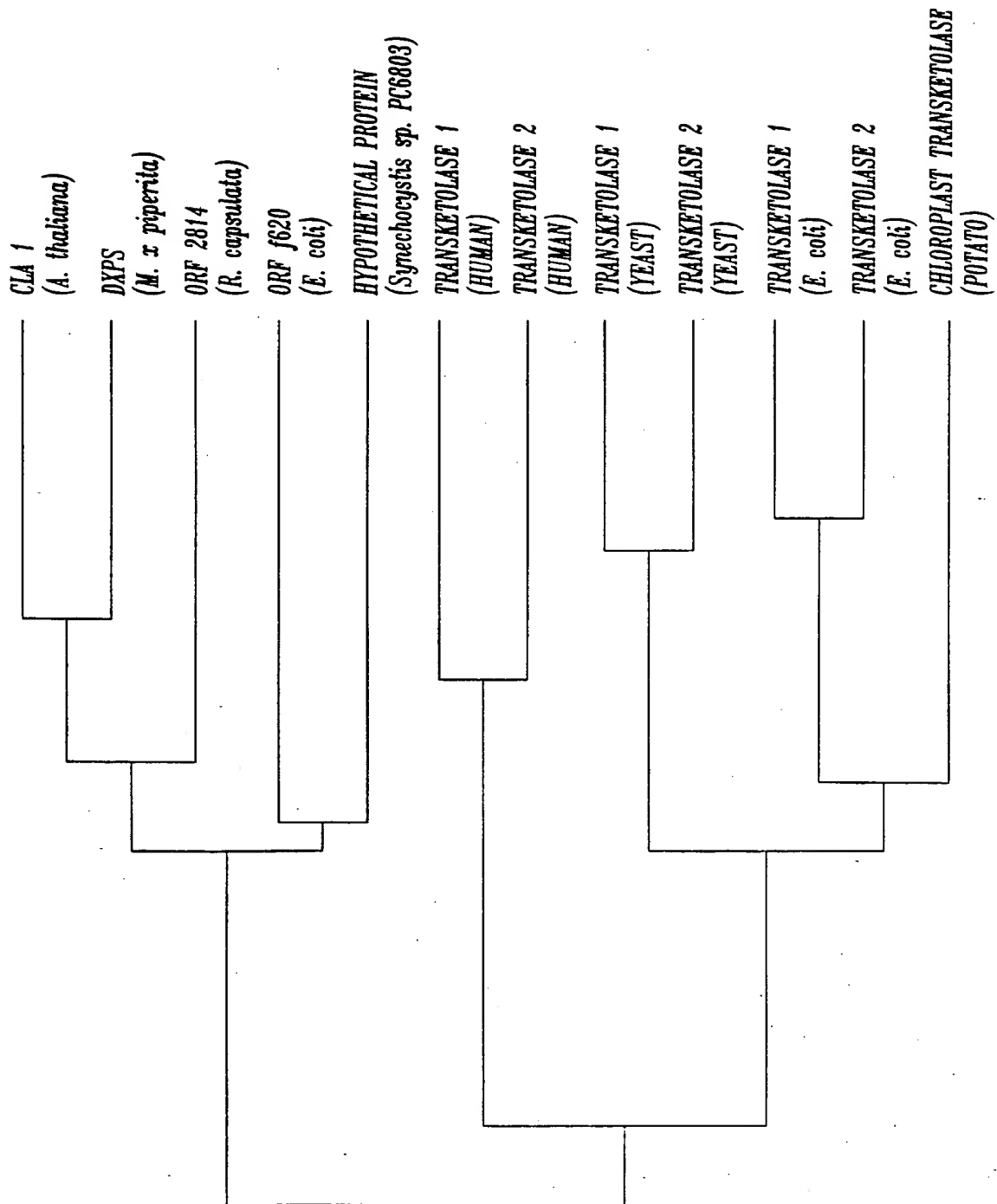
3/4

*Fig. 3*



4/4

Fig. 4



## SEQUENCE LISTING

<110> Croteau, Rodney B  
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Wildung, Mark R  
McCaskill, David G

<120> Nucleic and Amino Acid Sequences Relating to a Novel  
Transketolase, and Methods for the Expression Thereof

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          Met Ala Ser Ser Cys Gly Val Ile Lys
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agc agt ttc ttg cca tcg ctc cat tct gag gat tct acc ttc tta tca 159
Ser Ser Phe Leu Pro Ser Leu His Ser Glu Asp Ser Thr Phe Leu Ser

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675

680

685

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Val Gly Ala Leu Ser Lys Ala Leu Thr Lys Leu Gln Ala Ser Arg Lys	
270 275 280	
ttc cgg cag ctc cgc gaa gca gca aag agt atg act aag cag atg gga	975
Phe Arg Gln Leu Arg Glu Ala Ala Lys Ser Met Thr Lys Gln Met Gly	
285 290 295	
gca ccg gca cat gaa ata gct tcg aag ttg aca caa tac gtg aaa ggg	1023
Ala Pro Ala His Glu Ile Ala Ser Lys Leu Thr Gln Tyr Val Lys Gly	
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Met Met Gly Lys Pro Gly Ala Ser Leu Phe Glu Glu Leu Gly Ile Tyr	
315 320 325	
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Tyr Ile Gly Pro Val Asp Gly His Asn Val Glu Asp Leu Val Tyr Ile	
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Phe Lys Lys Val Lys Glu Met Pro Ala Pro Gly Pro Val Leu Ile His	
350 355 360	
atc atc acc gaa aaa ggc aaa ggc tac ccc cct gca gaa att gct gcc	1215
Ile Ile Thr Glu Lys Gly Lys Gly Tyr Pro Pro Ala Glu Ile Ala Ala	
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gac aaa atg cat ggg gtg gtg aag ttt gat gcg aaa act ggg aaa cag	1263
Asp Lys Met His Gly Val Val Lys Phe Asp Ala Lys Thr Gly Lys Gln	
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atg aag acg aag aac aag acg aag tca tac acc cag tac ttc gcc gag	1311
Met Lys Thr Lys Asn Lys Thr Lys Ser Tyr Thr Gln Tyr Phe Ala Glu	
395 400 405	

tct ctg gtg gcg gag gcg gag cac gac gac aag atc gtg gcg atc cac	1359
Ser Leu Val Ala Glu Ala Glu His Asp Asp Lys Ile Val Ala Ile His	
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Ala Ala Met Gly Gly Gly Thr Gly Leu Asn Ile Phe Gln Lys Gln Phe	
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Pro Asp Arg Cys Phe Asp Val Gly Ile Ala Glu Gln His Ala Val Thr	
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Phe Ala Ala Gly Met Ala Ala Glu Gly Leu Lys Pro Phe Cys Ala Ile	
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Tyr Ser Ser Phe Leu Gln Arg Gly Tyr Asp Gln Val Val His Asp Val	
475 480 485	
gac ctc cag aag ctc ccg gtc cgg ttc atg atg gat cgg gca gga gtc	1599
Asp Leu Gln Lys Leu Pro Val Arg Phe Met Met Asp Arg Ala Gly Val	
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Val Gly Ala Asp Gly Pro Thr His Cys Gly Ala Phe Asp Thr Thr Tyr	
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Met Ala Cys Leu Pro Asn Met Val Val Met Ala Pro Ser Asp Glu Ala	
525 530 535	
gag ctc atg aac atg atc gcc acc gcc gcc atc atc gac gac cga cct	1743
Glu Leu Met Asn Met Ile Ala Thr Ala Ala Ile Ile Asp Asp Arg Pro	
540 545 550	
agc tgc gtc cgg tac cct aga ggg aac ggc atc ggc gtc gct ctt ccg	1791
Ser Cys Val Arg Tyr Pro Arg Gly Asn Gly Ile Gly Val Ala Leu Pro	
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tcg aac aac aaa gga act cca tta gag att ggt aag gga aga atc ttg	1839
Ser Asn Asn Lys Gly Thr Pro Leu Glu Ile Gly Lys Gly Arg Ile Leu	
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aag gag ggg agc aaa gtt gcg att ctg gga ttc gga acc ata gtg cag	1887
Lys Glu Gly Ser Lys Val Ala Ile Leu Gly Phe Gly Thr Ile Val Gln	
590 595 600	
aac tgc atg gcg gcg gcg aat ctt ctc gaa caa cac gga atc tca gta	1935
Asn Cys Met Ala Ala Ala Asn Leu Leu Glu Gln His Gly Ile Ser Val	
605 610 615	
aca gta gcc gat gca aga ttc tgc aag cca ctc gat ggg gat ttg ata	1983
Thr Val Ala Asp Ala Arg Phe Cys Lys Pro Leu Asp Gly Asp Leu Ile	
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Lys Lys Leu Val Gln Glu His Glu Val Leu Ile Thr Val Glu Glu Gly	
635 640 645	
tcc atc ggt gga ttc agt gct cac att tct cat ttc ttg tcc ctc aat	2079
Ser Ile Gly Gly Phe Ser Ala His Ile Ser His Phe Leu Ser Leu Asn	
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ggc ttg ctc gat gga aac ctc aag tgg agg cca atg gtt ctt cca gat 2127  
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agg tac att gat cat gga gca cag agt gat caa ata gaa gaa gca ggg 2175  
 Arg Tyr Ile Asp His Gly Ala Gln Ser Asp Gln Ile Glu Glu Ala Gly  
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ctg agt cct aag cat att gca ggg act gtt gtt tca ttg att gga gga 2223  
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 715 720

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ccatggaaat tgggggagct gttctaaata attgttggtga tggcagcctt ttctacatgt 2456

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<213> Mentha piperita

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Ser Asn Asp Val Val Pro Ser Gly Asp Arg Leu Ser Arg Pro Lys Ser  
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Arg Ala Leu Ser Phe Thr Gly Glu Lys Pro Pro Ile Pro Ile Leu Asp  
 65 70 75 80

Thr Ile Asn Tyr Pro Asn His Met Lys Asn Leu Ser Val Glu Glu Leu  
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Ala Asn Leu Ala Asp Glu Leu Arg Glu Glu Ile Val Tyr Thr Val Ser  
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Lys Thr Gly Gly His Leu Ser Ser Ser Leu Gly Val Ser Glu Leu Thr  
 115 120 125

Val Ala Leu His His Val Phe Asn Thr Pro Asp Asp Lys Ile Ile Trp  
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Asp Val Gly His Gln Ala Tyr Pro His Lys Ile Leu Thr Gly Arg Arg  
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Ala Arg Met His Thr Ile Arg Gln Thr Phe Gly Leu Ala Gly Phe Pro  
 165 170 175

Lys Arg Asp Glu Ser Ala His Asp Ala Phe Gly Ala Gly His Ser Ser  
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 Thr Ser Ile Ser Ala Gly Leu Gly Met Ala Val Ala Arg Asp Leu Leu  
 195 200 205  
 Gln Lys Asn Asn His Val Ile Ser Val Ile Gly Asp Gly Ala Met Thr  
 210 215 220  
 Ala Gly Gln Ala Tyr Glu Ala Leu Asn Asn Ala Gly Phe Leu Asp Ser  
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 Asn Leu Ile Ile Val Leu Asn Asp Asn Lys Gln Val Ser Leu Pro Thr  
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 260 265 270  
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 Ser Lys Leu Thr Gln Tyr Val Lys Gly Met Met Gly Lys Pro Gly Ala  
 305 310 315 320  
 Ser Leu Phe Glu Glu Leu Gly Ile Tyr Tyr Ile Gly Pro Val Asp Gly  
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 His Asn Val Glu Asp Leu Val Tyr Ile Phe Lys Lys Val Lys Glu Met  
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 Pro Ala Pro Gly Pro Val Leu Ile His Ile Ile Thr Glu Lys Gly Lys  
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 Gly Tyr Pro Pro Ala Glu Ile Ala Ala Asp Lys Met His Gly Val Val  
 370 375 380  
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 385 390 395 400  
 Lys Ser Tyr Thr Gln Tyr Phe Ala Glu Ser Leu Val Ala Glu Ala Glu  
 405 410 415  
 His Asp Asp Lys Ile Val Ala Ile His Ala Ala Met Gly Gly Gly Thr  
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 Gly Ile Ala Glu Gln His Ala Val Thr Phe Ala Ala Gly Met Ala Ala  
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 Glu Gly Leu Lys Pro Phe Cys Ala Ile Tyr Ser Ser Phe Leu Gln Arg  
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 Gly Tyr Asp Gln Val Val His Asp Val Asp Leu Gln Lys Leu Pro Val  
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 Arg Phe Met Met Asp Arg Ala Gly Val Val Gly Ala Asp Gly Pro Thr  
 500 505 510  
 His Cys Gly Ala Phe Asp Thr Thr Tyr Met Ala Cys Leu Pro Asn Met

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 Thr Ala Ala Ile Ile Asp Asp Arg Pro Ser Cys Val Arg Tyr Pro Arg  
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 Gly Asn Gly Ile Gly Val Ala Leu Pro Ser Asn Asn Lys Gly Thr Pro  
 565                      570                      575  
 Leu Glu Ile Gly Lys Gly Arg Ile Leu Lys Glu Gly Ser Lys Val Ala  
 580                      585                      590  
 Ile Leu Gly Phe Gly Thr Ile Val Gln Asn Cys Met Ala Ala Ala Asn  
 595                      600                      605  
 Leu Leu Glu Gln His Gly Ile Ser Val Thr Val Ala Asp Ala Arg Phe  
 610                      615                      620  
 Cys Lys Pro Leu Asp Gly Asp Leu Ile Lys Lys Leu Val Gln Glu His  
 625                      630                      635                      640  
 Glu Val Leu Ile Thr Val Glu Glu Gly Ser Ile Gly Gly Phe Ser Ala  
 645                      650                      655  
 His Ile Ser His Phe Leu Ser Leu Asn Gly Leu Leu Asp Gly Asn Leu  
 660                      665                      670  
 Lys Trp Arg Pro Met Val Leu Pro Asp Arg Tyr Ile Asp His Gly Ala  
 675                      680                      685  
 Gln Ser Asp Gln Ile Glu Glu Ala Gly Leu Ser Pro Lys His Ile Ala  
 690                      695                      700  
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 gagagag atg gca tct tcc tgt gga gtt atc aag agc agt ttc ttg cca 169  
           Met Ala Ser Ser Cys Gly Val Ile Lys Ser Ser Phe Leu Pro  
           1                      5                      10  
 tcg ctc cat tct gag gat tct acc ttc tta tca cgt gct cct act tct 217  
 Ser Leu His Ser Glu Asp Ser Thr Phe Leu Ser Arg Ala Pro Thr Ser  
 15                      20                      25                      30

ctt ccc ctc aaa aat cat aag tta aat gtg gta gca gct ctc caa caa	265
Leu Pro Leu Lys Asn His Lys Leu Asn Val Val Ala Ala Leu Gln Gln	
35 40 45	
gat agt tcg aac gac gac gtc gtt cct agc gga gac agg ctg agc cgg	313
Asp Ser Ser Asn Asp Asp Val Val Pro Ser Gly Asp Arg Leu Ser Arg	
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ccg aaa tca aga gca ctg agt ttc acc gga gag aag cct ccc att cct	361
Pro Lys Ser Arg Ala Leu Ser Phe Thr Gly Glu Lys Pro Pro Ile Pro	
65 70 75	
ata ctg gac acc atc aac tac cct aat cac atg aaa aat ctt tcc gtc	409
Ile Leu Asp Thr Ile Asn Tyr Pro Asn His Met Lys Asn Leu Ser Val	
80 85 90	
gag gaa ctc gca aac cta gct gat gaa ctg agg gaa gag ata gtg tac	457
Glu Glu Leu Ala Asn Leu Ala Asp Glu Leu Arg Glu Glu Ile Val Tyr	
95 100 105 110	
acg gtg tcg aaa acc ggc ggc cat ctt agc tcg agc cta ggc gtg tcg	505
Thr Val Ser Lys Thr Gly Gly His Leu Ser Ser Ser Leu Gly Val Ser	
115 120 125	
gag ctc acc gtc gca ctt cat cac gtt ttc aac acg ccc gat gac aaa	553
Glu Leu Thr Val Ala Leu His His Val Phe Asn Thr Pro Asp Asp Lys	
130 135 140	
atc atc tgg gac gtc ggc cac cag gct tac cca cac aaa atc ttg acc	601
Ile Ile Trp Asp Val Gly His Gln Ala Tyr Pro His Lys Ile Leu Thr	
145 150 155	
ggg aga aga gcg aga atg cac aca att agg cag aca ttt gga tta gca	649
Gly Arg Arg Ala Arg Met His Thr Ile Arg Gln Thr Phe Gly Leu Ala	
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Gly Phe Pro Lys Arg Asp Glu Ser Ala His Asp Ala Phe Gly Ala Gly	
175 180 185 190	
cat agt tct acc agt att tct gct ggt tta ggg atg gcg gtg gcg aga	745
His Ser Ser Thr Ser Ile Ser Ala Gly Leu Gly Met Ala Val Ala Arg	
195 200 205	
gat tta ctg cag aag aac aac cac gtc ata tcg gtg atc ggc gac ggc	793
Asp Leu Leu Gln Lys Asn Asn His Val Ile Ser Val Ile Gly Asp Gly	
210 215 220	
gcc atg aca gct gga caa gcg tac gag gcc tta aac aac gcc gga ttc	841
Ala Met Thr Ala Gly Gln Ala Tyr Gln Ala Leu Asn Asn Ala Gly Phe	
225 230 235	
ctc gat tcg aat ctc ata atc gtt tta aac gac aac aag cag gtg tct	889
Leu Asp Ser Asn Leu Ile Ile Val Leu Asn Asp Asn Lys Gln Val Ser	
240 245 250	
cta ccc acg gcc acc gtc gac ggc cct gcg ccg ccg gtc gga gct ctg	937
Leu Pro Thr Ala Thr Val Asp Gly Pro Ala Pro Pro Val Gly Ala Leu	
255 260 265 270	
agc aaa gcc ctg acc aag ctg caa gcc agc aga aaa ttc cgg cag ctc	985
Ser Lys Ala Leu Thr Lys Leu Gln Ala Ser Arg Lys Phe Arg Gln Leu	
275 280 285	

cgc gaa gca gca aag agt atg act aag cag atg gga gca ccg gca cat	1033
Arg Glu Ala Ala Lys Ser Met Thr Lys Gln Met Gly Ala Pro Ala His	
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gaa ata gct tcg aag ttg aca caa tac gtg aaa ggg atg atg ggg aaa	1081
Glu Ile Ala Ser Lys Leu Thr Gln Tyr Val Lys Gly Met Met Gly Lys	
305 310 315	
cca ggc gct tca ctt ttc gaa gaa ctg ggg att tat tac atc gga cca	1129
Pro Gly Ala Ser Leu Phe Glu Glu Leu Gly Ile Tyr Tyr Ile Gly Pro	
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Val Asp Gly His Asn Val Glu Asp Leu Val Tyr Ile Phe Lys Lys Val	
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Lys Glu Met Pro Ala Pro Gly Pro Val Leu Ile His Ile Ile Thr Glu	
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aaa ggc aaa ggc tac ccc cct gca gaa att gct gcc gac aaa atg cat	1273
Lys Gly Lys Gly Tyr Pro Pro Ala Glu Ile Ala Ala Asp Lys Met His	
370 375 380	
ggg gtg gtg aag ttt gat gcg aaa act ggg aaa cag atg aag acg aag	1321
Gly Val Val Lys Phe Asp Ala Lys Thr Gly Lys Gln Met Lys Thr Lys	
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Asn Lys Thr Lys Ser Tyr Thr Gln Tyr Phe Ala Glu Ser Leu Val Ala	
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gag gcg gag cac gac gac aag atc gtg gcg atc cac gcc gcc atg ggg	1417
Glu Ala Glu His Asp Asp Lys Ile Val Ala Ile His Ala Ala Met Gly	
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Phe Asp Val Gly Ile Ala Glu Gln His Ala Val Thr Phe Ala Ala Gly	
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Met Ala Ala Glu Gly Leu Lys Pro Phe Cys Ala Ile Tyr Ser Ser Phe	
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Leu Gln Arg Gly Tyr Asp Gln Val Val His Asp Val Asp Leu Gln Lys	
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ctc ccg gtc cgg ttc atg atg gat cgg gca gga gtc gtc ggc gcc gac	1657
Leu Pro Val Arg Phe Met Met Asp Arg Ala Gly Val Val Gly Ala Asp	
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Gly Pro Thr His Cys Gly Ala Phe Asp Thr Thr Tyr Met Ala Cys Leu	
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Pro Asn Met Val Val Met Ala Pro Ser Asp Glu Ala Glu Leu Met Asn	
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 Met Ile Ala Thr Ala Ala Ile Ile Asp Asp Arg Pro Ser Cys Val Arg  
 545 550 555

tac cct aga ggg aac gcc atc ggc gtc gct ctt ccg tcg aac aac aaa 1849  
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gga act cca tta gag att ggt aag gga aga atc ttg aag gag ggg agc 1897  
 Gly Thr Pro Leu Glu Ile Gly Lys Gly Arg Ile Leu Lys Glu Gly Ser  
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aaa gtt gcg att ctg gga ttc gga acc ata gtg cag aac tgc atg gcg 1945  
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cag gag cat gaa gta ctc atc act gtt gaa gaa gga tcc atc ggg atc 2089  
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ctc gat gga aac ctc aag tgg agg cca atg gtt ctt cca gat agg tac 2185  
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 Pro Lys His Ile Ala Gly Thr Val Val Ser Leu Ile Gly Gly Gly Lys  
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gac agt ctt cat ttg att aat aat ttg taatattatt ttaatttatt 2328  
 Asp Ser Leu His Leu Ile Asn Asn Leu  
 720 725

tcttcgaaaa ggaaaagaga aaaaaatgga gtctgaattt gagcagctgc aaaaattctc 2388

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Ser Asn Asp Asp Val Val Pro Ser Gly Asp Arg Leu Ser Arg Pro Lys	50	55	60
Ser Arg Ala Leu Ser Phe Thr Gly Glu Lys Pro Pro Ile Pro Ile Leu	65	70	75
Asp Thr Ile Asn Tyr Pro Asn His Met Lys Asn Leu Ser Val Glu Glu	85	90	95
Leu Ala Asn Leu Ala Asp Glu Leu Arg Glu Glu Ile Val Tyr Thr Val	100	105	110
Ser Lys Thr Gly Gly His Leu Ser Ser Ser Leu Gly Val Ser Glu Leu	115	120	125
Thr Val Ala Leu His His Val Phe Asn Thr Pro Asp Asp Lys Ile Ile	130	135	140
Trp Asp Val Gly His Gln Ala Tyr Pro His Lys Ile Leu Thr Gly Arg	145	150	155
Arg Ala Arg Met His Thr Ile Arg Gln Thr Phe Gly Leu Ala Gly Phe	165	170	175
Pro Lys Arg Asp Glu Ser Ala His Asp Ala Phe Gly Ala Gly His Ser	180	185	190
Ser Thr Ser Ile Ser Ala Gly Leu Gly Met Ala Val Ala Arg Asp Leu	195	200	205
Leu Gln Lys Asn Asn His Val Ile Ser Val Ile Gly Asp Gly Ala Met	210	215	220
Thr Ala Gly Gln Ala Tyr Glu Ala Leu Asn Asn Ala Gly Phe Leu Asp	225	230	235
Ser Asn Leu Ile Ile Val Leu Asn Asp Asn Lys Gln Val Ser Leu Pro	245	250	255
Thr Ala Thr Val Asp Gly Pro Ala Pro Pro Val Gly Ala Leu Ser Lys	260	265	270
Ala Leu Thr Lys Leu Gln Ala Ser Arg Lys Phe Arg Gln Leu Arg Glu	275	280	285
Ala Ala Lys Ser Met Thr Lys Gln Met Gly Ala Pro Ala His Glu Ile	290	295	300
Ala Ser Lys Leu Thr Gln Tyr Val Lys Gly Met Met Gly Lys Pro Gly	305	310	315
Ala Ser Leu Phe Glu Glu Leu Gly Ile Tyr Tyr Ile Gly Pro Val Asp	325	330	335
Gly His Asn Val Glu Asp Leu Val Tyr Ile Phe Lys Lys Val Lys Glu	340	345	350

Met Pro Ala Pro Gly Pro Val Leu Ile His Ile Ile Thr Glu Lys Gly  
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 Lys Gly Tyr Pro Pro Ala Glu Ile Ala Ala Asp Lys Met His Gly Val  
 370 375 380  
 Val Lys Phe Asp Ala Lys Thr Gly Lys Gln Met Lys Thr Lys Asn Lys  
 385 390 395 400  
 Thr Lys Ser Tyr Thr Gln Tyr Phe Ala Glu Ser Leu Val Ala Glu Ala  
 405 410 415  
 Glu His Asp Asp Lys Ile Val Ala Ile His Ala Ala Met Gly Gly Gly  
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 Thr Gly Leu Asn Ile Phe Gln Lys Gln Phe Pro Asp Arg Cys Phe Asp  
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 Val Gly Ile Ala Glu Gln His Ala Val Thr Phe Ala Ala Gly Met Ala  
 450 455 460  
 Ala Glu Gly Leu Lys Pro Phe Cys Ala Ile Tyr Ser Ser Phe Leu Gln  
 465 470 475 480  
 Arg Gly Tyr Asp Gln Val Val His Asp Val Asp Leu Gln Lys Leu Pro  
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 565 570 575  
 Pro Leu Glu Ile Gly Lys Gly Arg Ile Leu Lys Glu Gly Ser Lys Val  
 580 585 590  
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 595 600 605  
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 Phe Cys Lys Pro Leu Asp Gly Asp Leu Ile Lys Lys Leu Val Gln Glu  
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 His Glu Val Leu Ile Thr Val Glu Glu Gly Ser Ile Gly Ile Gly Gly  
 645 650 655  
 Phe Ser Ala His Ile Ser His Phe Leu Ser Leu Asn Gly Leu Leu Asp  
 660 665 670  
 Gly Asn Leu Lys Trp Arg Pro Met Val Leu Pro Asp Arg Tyr Ile Asp  
 675 680 685

His Gly Ala Gln Ser Asp Gln Ile Glu Glu Ala Gly Leu Ser Pro Lys  
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Leu His Leu Ile Asn Asn Leu  
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<210> 10  
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 <212> PRT  
 <213> Artificial Sequence

<220>  
 <223> Description of Artificial Sequence: consensus  
 transketolase motif wherein Xaa at position 4 represents a sequence of 7 to 8  
 amino acids, Xaa at position 6 represents a sequence of 3 to 4 amino acids, and  
 Xaa at position 8 represents a sequence of 11 to 13 amino acids

<220>  
 <221> DOMAIN  
 <222> (1)..(10)

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 1 5 10

<210> 11  
 <211> 24  
 <212> PRT  
 <213> Artificial Sequence

<220>

<223> Description of Artificial Sequence: transketolase  
 motif from *Mentha piperita* wherein Xaa at position 3 represents Ala or Ser  
 Xaa at position 4 represents any amino acid, Xaa at position 6 represents Ala  
 or Gly, Xaa at position 8 represents Gln or Met, Xaa at position 10 represents  
 any amino acid, Xaa at position 13 represents any amino acid, Xaa at  
 position 15 represents Asn or His, Xaa at position 18 represents a sequence of  
 7 to 8 amino acids, Xaa at position 19 represents Ile or Val and Xaa at  
 position 20 represents Ile or Val

<220>

<221> DOMAIN

<222> (1)..(24)

<400> 11

Asp Gly Xaa Xaa Thr Xaa Gly Xaa Ala Xaa Glu Ala Xaa Asn Xaa Ala  
 1 5 10 15

Gly Xaa Xaa Xaa Leu Asn Asp Asn  
 20

<210> 12

<211> 1400

<212> DNA

<213> *Mentha piperita*

<400> 12

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 cactgagttt caccggagag aagcctccca ttctatact ggacaccatc aactacccta 240  
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## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US98/18231

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : C12N 1/21, 5/14, 15/29, 15/52, 15/82

US CL : 435/172.3, 252.3, 252.33, 320.1, 419; 536/23.2, 23.6

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 435/172.3, 252.3, 252.33, 320.1, 419; 536/23.2, 23.6

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS, STN, BIOSIS, EMBASE, AGRICOLA, CA, WPIDS

search terms: deoxyxylulose, synthase, transketolase, plant, DNA, cDNA, gene

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	MANDEL et al. CLA1, A Novel Gene Required for Chloroplast Development, is Highly Conserved in Evolution. The Plant Journal. 1996, Vol. 9, No. 5, pages 649-658, see especially figures 4-5, pages 651-652.	1-4,7-9, 13-18
X	BERNACCHIA et al. The Transketolase Gene Family of the Ressurrection Plant Craterostigma Plantaginueum: Differential Expression during the Rehydration Phase. The EMBO Journal. 1995. Vol. 14, No. 3, pages 610-618, see especially figure 1.	1-4,7,13-15
X	EP 723,017 (SCHMIDT et al) 13 January 1996, pages 8-12.	1-4,7,13-155

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:	*T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
*A* document defining the general state of the art which is not considered to be of particular relevance	*X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
*E* earlier document published on or after the international filing date	*Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
*L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	*&* document member of the same patent family
*O* document referring to an oral disclosure, use, exhibition or other means	
*P* document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

24 NOVEMBER 1998

Date of mailing of the international search report

30 DEC 1998

Name and mailing address of the ISA/US  
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## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US98/18231

## C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 723 017 A2 (SCHMIDT et al) 13 January 1996, pages 8-12.	1-4,7,13-155
X	Database BIOSIS on STN, No. 99593777, SCHENK et al. 'Molecular Evolutionary Analysis of the Thiamine- Diphosphate- Dependent Enzyme, Transketolase.' (Journal of Molecular Evolution. 1997. Vol. 44, No. 5, pages 552-572).	1-4,7,13-15



# INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US98/18231

## Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:  
because they relate to subject matter not required to be searched by this Authority, namely:
  
2. ☐ Claims Nos.:  
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
  
3. ☐ Claims Nos.:  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

## Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Please See Extra Sheet.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
  
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.  
☐ No protest accompanied the payment of additional search fees.

# INTERNATIONAL SEARCH REPORT

International application No.

PCT/US98/18231

## BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING

This ISA found multiple inventions as follows:

This application contains the following inventions or groups of inventions which are not so linked as to form a single inventive concept under PCT Rule 13.1. In order for all inventions to be searched, the appropriate additional search fees must be paid.

Group I, claim(s) 1-7, 13-18, drawn to DNA, vectors, host cells, method of altering DXPS activity.  
Group II, claim(s) 8-12, drawn to protein.

The inventions listed as Groups I and II do not relate to a single inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons:

The broad claims read on isolated nucleic acid molecules which encompass the *Arabidopsis* DXPS nucleic acid disclosed by Mandel (Plant J. 9: 649-658, 1996), particularly in view of the language "at least a functional portion of" or "at least a portion of." Therefore, there is no special technical feature which links the DNA and the protein molecules, and because the DNA and protein molecules differ in composition, structure, and function, the two groups do not form a single inventive concept under PCT Rule 13.1.